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Physics

اعداد

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Introduction to Electronics

1

CHAPTER OUTLINE

1–1 The Atom
1–2 Materials Used in Electronics
1–3 Current in Semiconductors
1–4 *N*-Type and *P*-Type Semiconductors
1–5 The *PN* Junction
GreenTech Application 1: *Solar Power*

CHAPTER OBJECTIVES

- Describe the structure of an atom
- Discuss insulators, conductors, and semiconductors and how they differ
- Describe how current is produced in a semiconductor
- Describe the properties of *n*-type and *p*-type semiconductors
- Describe how a *pn* junction is formed

KEY TERMS

- Atom
- Proton
- Electron
- Shell
- Valence
- Ionization
- Free electron
- Orbital
- Insulator
- Conductor
- Semiconductor
- Silicon
- Crystal
- Hole
- Doping
- *PN* junction
- Barrier potential

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INTRODUCTION

Electronic devices such as diodes, transistors, and integrated circuits are made of a semiconductive material. To understand how these devices work, you should have a basic knowledge of the structure of atoms and the interaction of atomic particles. An important concept introduced in this chapter is that of the *pn* junction that is formed when two different types of semiconductive material are joined. The *pn* junction is fundamental to the operation of devices such as the solar cell, the diode, and certain types of transistors.

1–1 THE ATOM

All matter is composed of atoms; all atoms consist of electrons, protons, and neutrons except normal hydrogen, which does not have a neutron. Each element in the periodic table has a unique atomic structure, and all atoms within a given element have the same number of protons. At first, the atom was thought to be a tiny indivisible sphere. Later it was shown that the atom was not a single particle but was made up of a small dense nucleus around which electrons orbit at great distances from the nucleus, similar to the way planets orbit the sun. Niels Bohr proposed that the electrons in an atom circle the nucleus in different obits, similar to the way planets orbit the sun in our solar system. The Bohr model is often referred to as the planetary model. Another view of the atom called the *quantum model* is considered a more accurate representation, but it is difficult to visualize. For most practical purposes in electronics, the Bohr model suffices and is commonly used because it is easy to visualize.

After completing this section, you should be able to

- **Describe the structure of an atom**
  - Discuss the Bohr model of an atom
  - Define *electron, proton, neutron,* and *nucleus*
- Define *atomic number*
- Discuss electron shells and orbits
  - Explain energy levels
- Define *valence electron*
- Discuss ionization
  - Define *free electron* and *ion*
- Discuss the basic concept of the quantum model of the atom

The Bohr Model

An **atom*** is the smallest particle of an element that retains the characteristics of that element. Each of the known 118 elements has atoms that are different from the atoms of all other elements. This gives each element a unique atomic structure. According to the classical Bohr model, atoms have a planetary type of structure that consists of a central nucleus surrounded by orbiting electrons, as illustrated in Figure 1–1. The **nucleus** consists of positively charged particles called **protons** and uncharged particles called **neutrons.** The basic particles of negative charge are called **electrons**.

Each type of atom has a certain number of electrons and protons that distinguishes it from the atoms of all other elements. For example, the simplest atom is that of hydrogen, which has one proton and one electron, as shown in Figure 1–2(a). As another example, the helium atom, shown in Figure 1–2(b), has two protons and two neutrons in the nucleus and two electrons orbiting the nucleus.

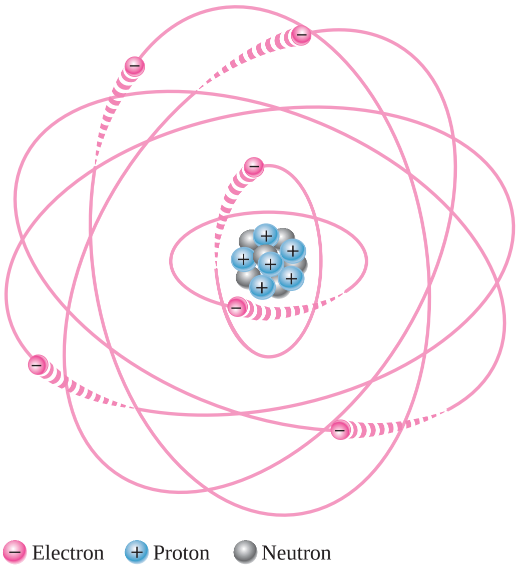
HISTORY NOTE

Niels Henrik David Bohr (October 7, 1885–November 18, 1962) was a Danish physicist, who made important contributions to understanding the structure of the atom and quantum mechanics by postulating the "planetary" model of the atom. He received the Nobel prize in physics in 1922. Bohr drew upon the work or collaborated with scientists such as Dalton, Thomson, and Rutherford, among others and has been described as one of the most influential physicists of the 20th century.

Atomic Number

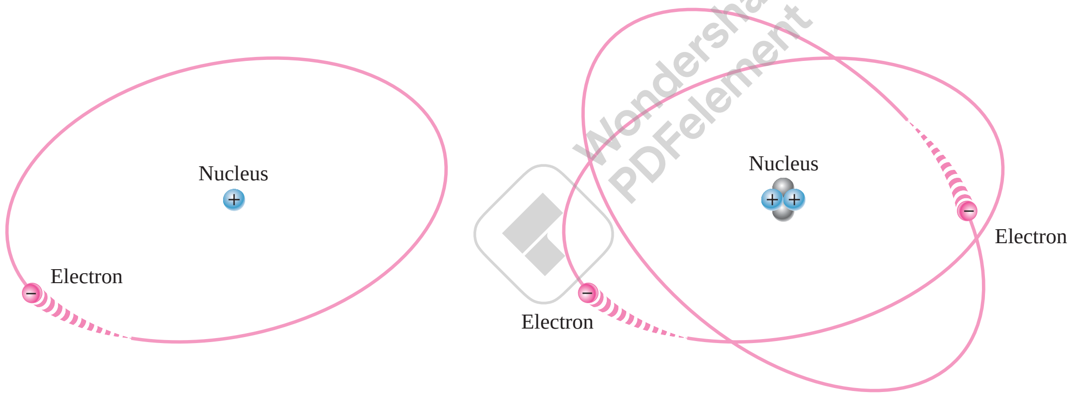
All elements are arranged in the periodic table of the elements in order according to their atomic number. The **atomic number** equals the number of protons in the nucleus, which is the same as the number of electrons in an electrically balanced (neutral) atom. For example, hydrogen has an atomic number of 1 and helium has an atomic number of 2. In their normal (or neutral) state, all atoms of a given element have the same number of electrons as protons; the positive charges cancel the negative charges, and the atom has a net charge of zero.

***All bold terms are in the end-of-book glossary. The bold terms in color are key terms and are also defined at the end of the chapter.**



▲ **FIGURE 1–1**

The Bohr model of an atom showing electrons in orbits around the nucleus, which consists of protons and neutrons. The "tails" on the electrons indicate motion.



(a) Hydrogen atom (b) Helium atom

▲ **FIGURE 1–2**

Two simple atoms, hydrogen and helium.

Atomic numbers of all the elements are shown on the periodic table of the elements in Figure 1–3.

Electrons and Shells

Energy Levels Electrons orbit the nucleus of an atom at certain distances from the nucleus. Electrons near the nucleus have less energy than those in more distant orbits. Only discrete (separate and distinct) values of electron energies exist within atomic structures. Therefore, electrons must orbit only at discrete distances from the nucleus.

Each discrete distance (**orbit**) from the nucleus corresponds to a certain energy level. In an atom, the orbits are grouped into energy levels known as **shells**. A given atom has a fixed number of shells. Each shell has a fixed maximum number of electrons. The shells (energy levels) are designated 1, 2, 3, and so on, with 1 being closest to the nucleus. The Bohr model of the silicon atom is shown in Figure 1–4. Notice that there are 14 electrons and 14 each of protons and neutrons in the nucleus.

Helium Atomic number = 2

Silicon Atomic number = 14

1 **H**																	2 **He**
3 **Li**	4 **Be**											5 **B**	6 **C**	7 **N**	8 **O**	9 **F**	10 **Ne**
11 **Na**	12 **Mg**											13 **Al**	14 **Si**	15 **P**	16 **S**	17 **Cl**	18 **Ar**
19 **K**	20 **Ca**	21 **Sc**	22 **Ti**	23 **V**	24 **Cr**	25 **Mn**	26 **Fe**	27 **Co**	28 **Ni**	29 **Cu**	30 **Zn**	31 **Ga**	32 **Ge**	33 **As**	34 **Se**	35 **Br**	36 **Kr**
37 **Rb**	38 **Sr**	39 **Y**	40 **Zr**	41 **Nb**	42 **Mo**	43 **Tc**	44 **Ru**	45 **Rh**	46 **Pd**	47 **Ag**	48 **Cd**	49 **In**	50 **Sn**	51 **Sb**	52 **Te**	53 **I**	54 **Xe**
55 **Cs**	56 **Ba**	*	72 **Hf**	73 **Ta**	74 **W**	75 **Re**	76 **Os**	77 **Ir**	78 **Pt**	79 **Au**	80 **Hg**	81 **Tl**	82 **Pb**	83 **Bi**	84 **Po**	85 **At**	86 **Rn**
87 **Fr**	88 **Ra**	**	104 **Rf**	105 **Db**	106 **Sg**	107 **Bh**	108 **Hs**	109 **Mt**	110 **Ds**	111 **Rg**	112 **Cp**	113 **Uut**	114 **Uuq**	115 **Uup**	116 **Uuh**	117 **Uus**	118 **Uuo**

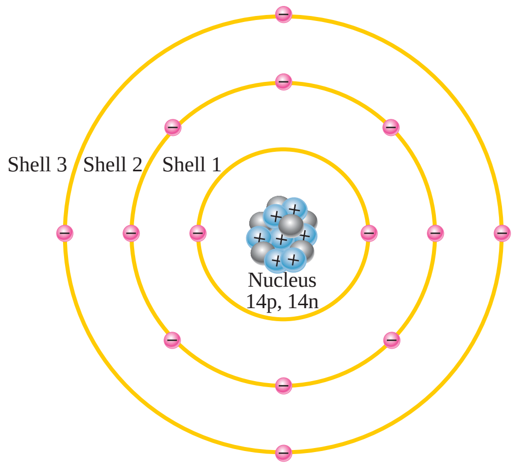
57 **La**	58 **Ce**	59 **Pr**	60 **Nd**	61 **Pm**	62 **Sm**	63 **Eu**	64 **Gd**	65 **Tb**	66 **Dy**	67 **Ho**	68 **Er**	69 **Tm**	70 **Yb**	71 **Lu**
89 **Ac**	90 **Th**	91 **Pa**	92 **U**	93 **Np**	94 **Pu**	95 **Am**	96 **Cm**	97 **Bk**	98 **Cf**	99 **Es**	100 **Fm**	101 **Md**	102 **No**	103 **Lr**

▲ **FIGURE 1–3**

The periodic table of the elements. Some tables also show atomic mass.

▶ **FIGURE 1–4**

Illustration of the Bohr model of the silicon atom.



The Maximum Number of Electrons in Each Shell The maximum number of electrons (N_e) that can exist in each shell of an atom is a fact of nature and can be calculated by the formula,

Equation 1–1

$$N_e = 2n^2$$

where n is the number of the shell. The maximum number of electrons that can exist in the innermost shell (shell 1) is

$$N_e = 2n^2 = 2(1)^2 = 2$$

The maximum number of electrons that can exist in shell 2 is

$$N_e = 2n^2 = 2(2)^2 = 2(4) = 8$$

The maximum number of electrons that can exist in shell 3 is

$$N_e = 2n^2 = 2(3)^2 = 2(9) = 18$$

The maximum number of electrons that can exist in shell 4 is

$$N_e = 2n^2 = 2(4)^2 = 2(16) = 32$$

Valence Electrons

Electrons that are in orbits farther from the nucleus have higher energy and are less tightly bound to the atom than those closer to the nucleus. This is because the force of attraction between the positively charged nucleus and the negatively charged electron decreases with increasing distance from the nucleus. Electrons with the highest energy exist in the outermost shell of an atom and are relatively loosely bound to the atom. This outermost shell is known as the **valence** shell and electrons in this shell are called *valence electrons.* These valence electrons contribute to chemical reactions and bonding within the structure of a material and determine its electrical properties. When a valence electron gains sufficient energy from an external source, it can break free from its atom. This is the basis for conduction in materials.

FYI

Atoms are extremely small and cannot be seen even with the strongest optical microscopes; however, a scanning tunneling microscope can detect a single atom. The nucleus is so small and the electrons orbit at such distances that the atom is mostly empty space. To put it in perspective, if the proton in a hydrogen atom were the size of a golf ball, the electron orbit would be approximately one mile away.

Protons and neutrons are approximately the same mass. The mass of an electron is 1/1836 of a proton. Within protons and neutrons there are even smaller particles called quarks.

Ionization

When an atom absorbs energy from a heat source or from light, for example, the energies of the electrons are raised. The valence electrons possess more energy and are more loosely bound to the atom than inner electrons, so they can easily jump to higher energy shells when external energy is absorbed by the atom.

If a valence electron acquires a sufficient amount of energy, called *ionization energy,* it can actually escape from the outer shell and the atom's influence. The departure of a valence electron leaves a previously neutral atom with an excess of positive charge (more protons than electrons). The process of losing a valence electron is known as **ionization**, and the resulting positively charged atom is called a *positive ion.* For example, the chemical symbol for hydrogen is H. When a neutral hydrogen atom loses its valence electron and becomes a positive ion, it is designated H^+. The escaped valence electron is called a **free electron**.

The reverse process can occur in certain atoms when a free electron collides with the atom and is captured, releasing energy. The atom that has acquired the extra electron is called a *negative ion*. The ionization process is not restricted to single atoms. In many chemical reactions, a group of atoms that are bonded together can lose or acquire one or more electrons.

For some nonmetallic materials such as chlorine, a free electron can be captured by the neutral atom, forming a negative ion. In the case of chlorine, the ion is more stable than the neutral atom because it has a filled outer shell. The chlorine ion is designated as Cl^-.

The Quantum Model

Although the Bohr model of an atom is widely used because of its simplicity and ease of visualization, it is not a complete model. The quantum model, a more recent model, is considered to be more accurate. The quantum model is a statistical model and very difficult to understand or visualize. Like the Bohr model, the quantum model has a nucleus of protons and neutrons surrounded by electrons. Unlike the Bohr model, the electrons in the quantum model do not exist in precise circular orbits as particles. Two important theories underlie the quantum model: the wave-particle duality and the uncertainty principle.

- *Wave-particle duality.* Just as light can be both a wave and a particle **(photon),** electrons are thought to exhibit a dual characteristic. The velocity of an orbiting electron is considered to be its wavelength, which interferes with neighboring electron waves by amplifying or canceling each other.

FYI

De Broglie showed that every particle has wave characteristics. Schrodiger developed a wave equation for electrons.

- *Uncertainly principle.* As you know, a wave is characterized by peaks and valleys; therefore, electrons acting as waves cannot be precisely identified in terms of their position. According to Heisenberg, it is impossible to determine simultaneously both the position and velocity of an electron with any degree of accuracy or certainty. The result of this principle produces a concept of the atom with *probability clouds,* which are mathematical descriptions of where electrons in an atom are most likely to be located.

In the quantum model, each shell or energy level consists of up to four subshells called **orbitals**, which are designated *s*, *p*, *d*, and *f*. Orbital *s* can hold a maximum of two electrons, orbital *p* can hold six electrons, orbital *d* can hold ten electrons, and orbital *f* can hold fourteen electrons. Each atom can be described by an electron configuration table that shows the shells or energy levels, the orbitals, and the number of electrons in each orbital. For example, the electron configuration table for the nitrogen atom is given in Table 1–1. The first full-size number is the shell or energy level, the letter is the orbital, and the exponent is the number of electrons in the orbital.

▶ **TABLE 1–1**

Electron configuration table for nitrogen.

NOTATION	EXPLANATION
$1s^2$	2 electrons in shell 1, orbital *s*
$2s^2$ $2p^3$	5 electrons in shell 2: 2 in orbital *s*, 3 in orbital *p*

Atomic orbitals do not resemble a discrete circular path for the electron as depicted in Bohr's planetary model. In the quantum picture, each shell in the Bohr model is a three-dimensional space surrounding the atom that represents the mean (average) energy of the electron cloud. The term **electron cloud** (probability cloud) is used to describe the area around an atom's nucleus where an electron will probably be found.

EXAMPLE 1–1

Using the atomic number from the periodic table in Figure 1–3, describe a silicon (Si) atom using an electron configuration table.

Solution The atomic number of silicon is 14. This means that there are 14 protons in the nucleus. Since there is always the same number of electrons as protons in a neutral atom, there are also 14 electrons. As you know, there can be up to two electrons in shell 1, eight in shell 2, and eighteen in shell 3. Therefore, in silicon there are two electrons in shell 1, eight electrons in shell 2, and four electrons in shell 3 for a total of 14 electrons. The electron configuration table for silicon is shown in Table 1–2.

▶ **TABLE 1–2**

NOTATION	EXPLANATION
$1s^2$	2 electrons in shell 1, orbital *s*
$2s^2$ $2p^6$	8 electrons in shell 2: 2 in orbital *s*, 6 in orbital *p*
$3s^2$ $3p^2$	4 electrons in shell 3: 2 in orbital *s*, 2 in orbital *p*

*Related Problem** Develop an electron configuration table for the germanium (Ge) atom in the periodic table.

*Answers can be found at www.pearsonhighered.com/floyd.

In a three-dimensional representation of the quantum model of an atom, the *s*-orbitals are shaped like spheres with the nucleus in the center. For energy level 1, the sphere is "solid" but for energy levels 2 or more, each single *s*-orbital is composed of spherical surfaces that are nested shells. A *p*-orbital for shell 2 has the form of two ellipsoidal lobes with a point of tangency at the nucleus (sometimes referred to as a dumbbell shape.) The three *p*-orbitals in each energy level are oriented at right angles to each other. One is oriented on the *x*-axis, one on the *y*-axis, and one on the *z*-axis. For example, a view of the quantum model of a sodium atom (Na) that has 11 electrons is shown in Figure 1–5. The three axes are shown to give you a 3-D perspective.

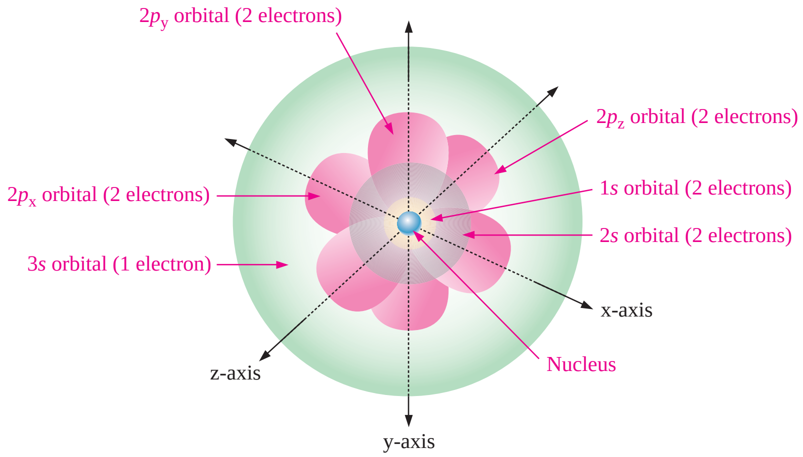


FIGURE 1–5

Three-dimensional quantum model of the sodium atom, showing the orbitals and number of electrons in each orbital.

SECTION 1–1 CHECKUP
Answers can be found at www.pearsonhighered.com/floyd.

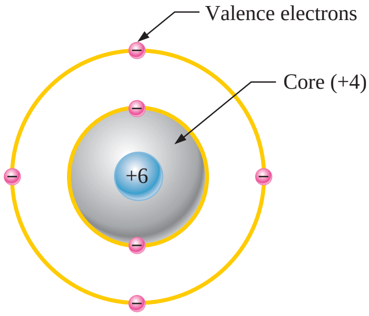
1. Describe the Bohr model of the atom.
2. Define *electron*.
3. What is the nucleus of an atom composed of? Define each component.
4. Define *atomic number*.
5. Discuss electron shells and orbits and their energy levels.
6. What is a valence electron?
7. What is a free electron?
8. Discuss the difference between positive and negative ionization.
9. Name two theories that distinguish the quantum model.

1–2 MATERIALS USED IN ELECTRONICS

In terms of their electrical properties, materials can be classified into three groups: conductors, semiconductors, and insulators. When atoms combine to form a solid, crystalline material, they arrange themselves in a symmetrical pattern. The atoms within the crystal structure are held together by covalent bonds, which are created by the interaction of the valence electrons of the atoms. Silicon is a crystalline material.

After completing this section, you should be able to

- **Discuss insulators, conductors, and semiconductors and how they differ**
  - Define the *core* of an atom ◆ Describe the carbon atom ◆ Name two types each of semiconductors, conductors, and insulators
- Explain the band gap
  - Define *valence band* and *conduction band* ◆ Compare a semiconductor atom to a conductor atom
- Discuss silicon and gemanium atoms
- Explain covalent bonds
  - Define *crystal*



▲ FIGURE 1–6

Diagram of a carbon atom.

Insulators, Conductors, and Semiconductors

All materials are made up of atoms. These atoms contribute to the electrical properties of a material, including its ability to conduct electrical current.

For purposes of discussing electrical properties, an atom can be represented by the valence shell and a **core** that consists of all the inner shells and the nucleus. This concept is illustrated in Figure 1–6 for a carbon atom. Carbon is used in some types of electrical resistors. Notice that the carbon atom has four electrons in the valence shell and two electrons in the inner shell. The nucleus consists of six protons and six neutrons, so the +6 indicates the positive charge of the six protons. The core has a net charge of +4 (+6 for the nucleus and −2 for the two inner-shell electrons).

Insulators An **insulator** is a material that does not conduct electrical current under normal conditions. Most good insulators are compounds rather than single-element materials and have very high resistivities. Valence electrons are tightly bound to the atoms; therefore, there are very few free electrons in an insulator. Examples of insulators are rubber, plastics, glass, mica, and quartz.

Conductors A **conductor** is a material that easily conducts electrical current. Most metals are good conductors. The best conductors are single-element materials, such as copper (Cu), silver (Ag), gold (Au), and aluminum (Al), which are characterized by atoms with only one valence electron very loosely bound to the atom. These loosely bound valence electrons become free electrons. Therefore, in a conductive material the free electrons are valence electrons.

Semiconductors A **semiconductor** is a material that is between conductors and insulators in its ability to conduct electrical current. A semiconductor in its pure (intrinsic) state is neither a good conductor nor a good insulator. Single-element semiconductors are antimony (Sb), arsenic (As), astatine (At), boron (B), polonium (Po), tellurium (Te), silicon (Si), and germanium (Ge). Compound semiconductors such as gallium arsenide, indium phosphide, gallium nitride, silicon carbide, and silicon germanium are also commonly used. The single-element semiconductors are characterized by atoms with four valence electrons. Silicon is the most commonly used semiconductor.

Band Gap

Recall that the valence shell of an atom represents a band of energy levels and that the valence electrons are confined to that band. When an electron acquires enough additional energy, it can leave the valence shell, become a *free electron*, and exist in what is known as the *conduction band*.

The difference in energy between the valence band and the conduction band is called an *energy gap* or **band gap**. This is the amount of energy that a valence electron must have in order to jump from the valence band to the conduction band. Once in the conduction band, the electron is free to move throughout the material and is not tied to any given atom.

Figure 1–7 shows energy diagrams for insulators, semiconductors, and conductors. The energy gap or band gap is the difference between two energy levels and is "not allowed" in quantum theory. It is a region in insulators and semiconductors where no electron states exist. Although an electron may not exist in this region, it can "jump" across it under certain conditions. For insulators, the gap can be crossed only when breakdown conditions occur—as when a very high voltage is applied across the material. The band gap is illustrated in Figure 1–7(a) for insulators. In semiconductors the band gap is smaller, allowing an electron in the valence band to jump into the conduction band if it absorbs a photon. The band gap depends on the semiconductor material. This is illustrated in Figure 1–7(b). In conductors, the conduction band and valence band overlap, so there is no gap, as shown in Figure 1–7(c). This means that electrons in the valence band move freely into the conduction band, so there are always electrons available as free electrons.

F Y I

Next to silicon, the second most common semiconductive material is gallium arsenide, GaAs. This is a crystalline compound, not an element. Its properties can be controlled by varying the relative amount of gallium and arsenic.

GaAs has the advantage of making semiconductor devices that respond very quickly to electrical signals. This makes it better than silicon for applications like amplifying the high frequency (1 GHz to 10 GHz) signals from TV satellites, etc. The main disadvantage of GaAs is that it is more difficult to make and the chemicals involved are quite often toxic!

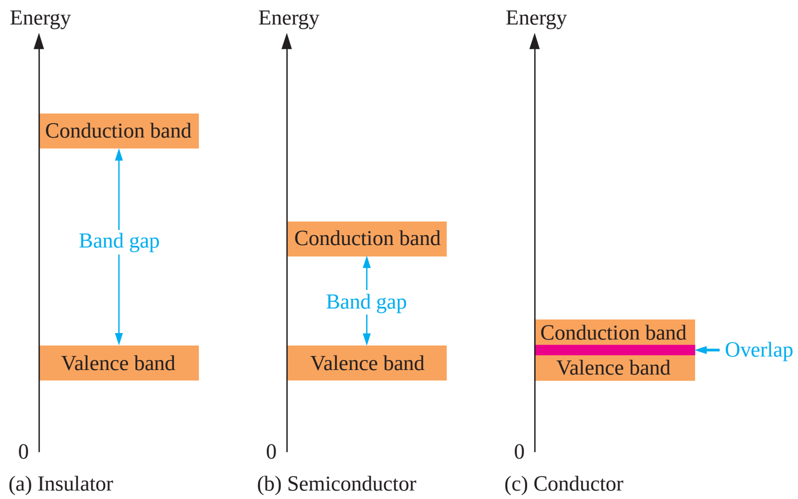


FIGURE 1–7

Energy diagrams for the three types of materials.

Comparison of a Semiconductor Atom to a Conductor Atom

Silicon is a semiconductor and copper is a conductor. Bohr diagrams of the silicon atom and the copper atom are shown in Figure 1–8. Notice that the core of the silicon atom has a net charge of +4 (14 protons − 10 electrons) and the core of the copper atom has a net charge of +1 (29 protons − 28 electrons). The core includes everything except the valence electrons.

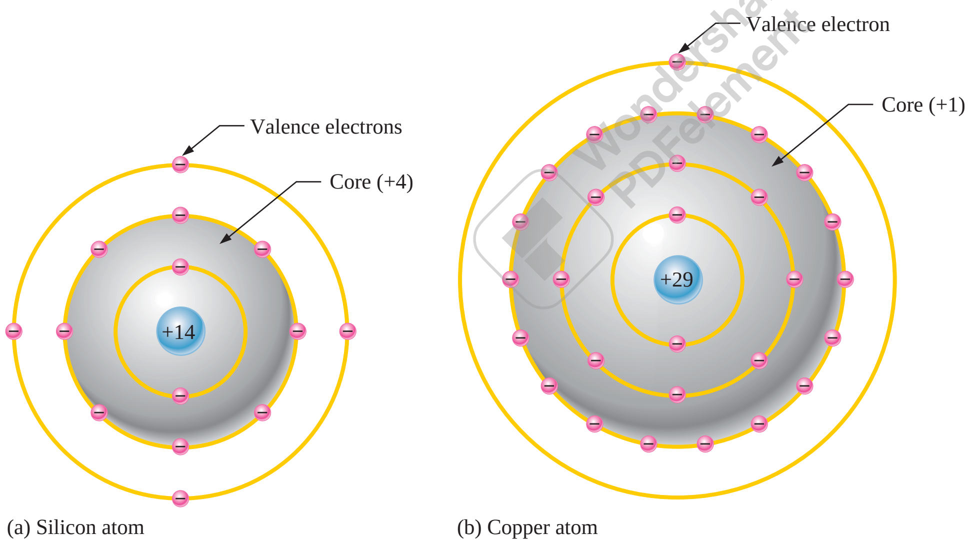


FIGURE 1–8

Bohr diagrams of the silicon and copper atoms.

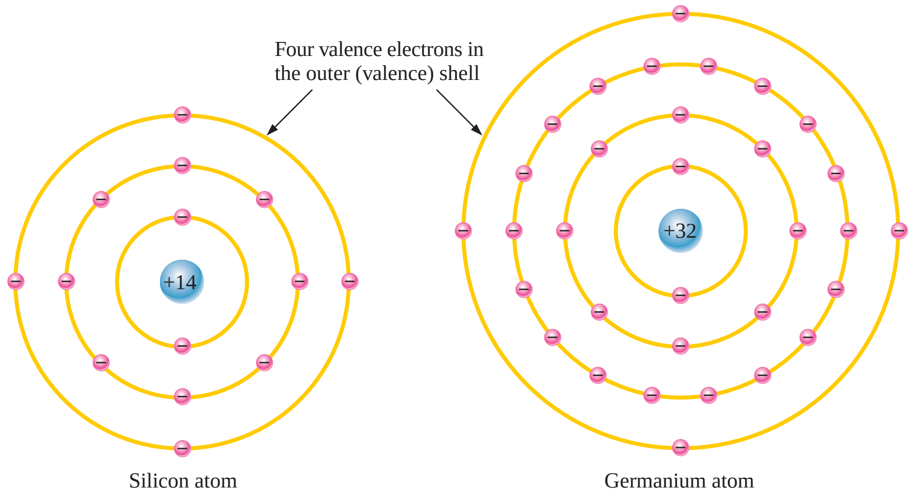
The valence electron in the copper atom "feels" an attractive force of +1 compared to a valence electron in the silicon atom which "feels" an attractive force of +4. Therefore, there is more force trying to hold a valence electron to the atom in silicon than in copper. The copper's valence electron is in the fourth shell, which is a greater distance from its nucleus than the silicon's valence electron in the third shell. Recall that electrons farthest from the nucleus have the most energy. The valence electron in copper has more energy than the valence electron in silicon. This means that it is easier for valence electrons in copper to acquire enough additional energy to escape from their atoms and become free electrons than it is in silicon. In fact, large numbers of valence electrons in copper already have sufficient energy to be free electrons at normal room temperature.

Silicon and Germanium

The atomic structures of silicon and germanium are compared in Figure 1–9. **Silicon** is used in diodes, transistors, integrated circuits, and other semiconductor devices. Notice that both silicon and **germanium** have the characteristic four valence electrons.

▶ FIGURE 1–9

Diagrams of the silicon and germanium atoms.

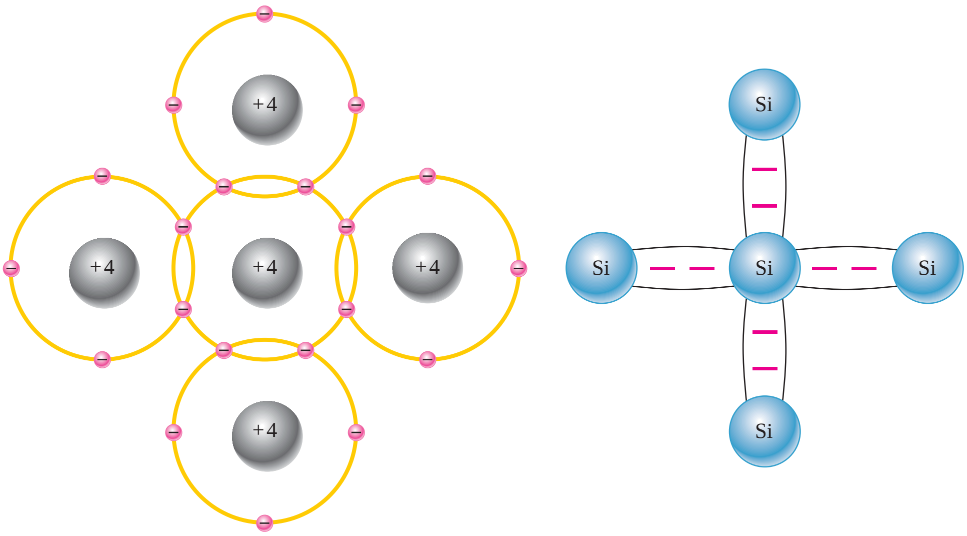


The valence electrons in germanium are in the fourth shell while those in silicon are in the third shell, closer to the nucleus. This means that the germanium valence electrons are at higher energy levels than those in silicon and, therefore, require a smaller amount of additional energy to escape from the atom. This property makes germanium more unstable at high temperatures and results in excessive reverse current. This is why silicon is a more widely used semiconductive material.

Covalent Bonds Figure 1–10 shows how each silicon atom positions itself with four adjacent silicon atoms to form a silicon **crystal**. A silicon (Si) atom with its four valence electrons shares an electron with each of its four neighbors. This effectively creates eight shared valence electrons for each atom and produces a state of chemical stability. Also, this sharing of valence electrons produces the **covalent** bonds that hold the atoms together; each valence electron is attracted equally by the two adjacent atoms which share it. Covalent bonding in an intrinsic silicon crystal is shown in Figure 1–11. An **intrinsic** crystal is one that has no impurities. Covalent bonding for germanium is similar because it also has four valence electrons.

▶ FIGURE 1–10

Illustration of covalent bonds in silicon.



(a) The center silicon atom shares an electron with each of the four surrounding silicon atoms, creating a covalent bond with each. The surrounding atoms are in turn bonded to other atoms, and so on.

(b) Bonding diagram. The red negative signs represent the shared valence electrons.

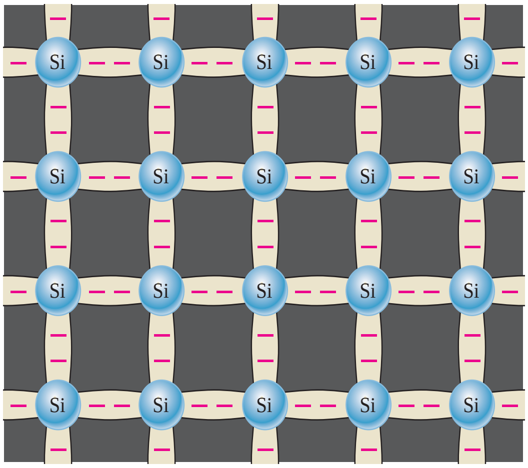


FIGURE 1–11

Covalent bonds in a silicon crystal.

SECTION 1–2 CHECKUP

1. What is the basic difference between conductors and insulators?
2. How do semiconductors differ from conductors and insulators?
3. How many valence electrons does a conductor such as copper have?
4. How many valence electrons does a semiconductor have?
5. Name three of the best conductive materials.
6. What is the most widely used semiconductive material?
7. Why does a semiconductor have fewer free electrons than a conductor?
8. How are covalent bonds formed?
9. What is meant by the term *intrinsic*?
10. What is a crystal?

1–3 CURRENT IN SEMICONDUCTORS

The way a material conducts electrical current is important in understanding how electronic devices operate. You can't really understand the operation of a device such as a diode or transistor without knowing something about current in semiconductors.

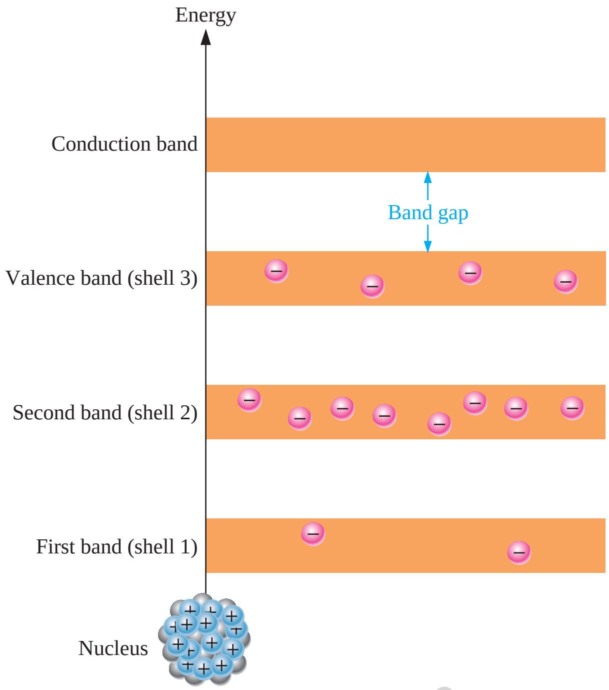
After completing this section, you should be able to

- **Describe how current is produced in a semiconductor**
- Discuss conduction electrons and holes
  - Explain an electron-hole pair
  - Discuss recombination
- Explain electron and hole current

As you have learned, the electrons of an atom can exist only within prescribed energy bands. Each shell around the nucleus corresponds to a certain energy band and is separated from adjacent shells by band gaps, in which no electrons can exist. Figure 1–12 shows the energy band diagram for an unexcited (no external energy such as heat) atom in a pure silicon crystal. This condition occurs *only* at a temperature of absolute 0 Kelvin.

▶ FIGURE 1–12

Energy band diagram for an unexcited atom in a pure (intrinsic) silicon crystal. There are no electrons in the conduction band.

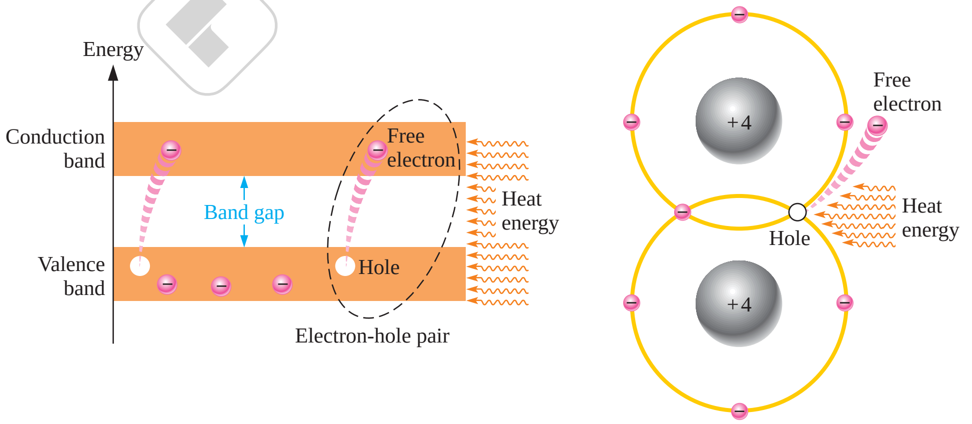


Conduction Electrons and Holes

An intrinsic (pure) silicon crystal at room temperature has sufficient heat (thermal) energy for some valence electrons to jump the gap from the valence band into the conduction band, becoming free electrons. Free electrons are also called **conduction electrons.** This is illustrated in the energy diagram of Figure 1–13(a) and in the bonding diagram of Figure 1–13(b).

▶ FIGURE 1–13

Creation of electron-hole pairs in a silicon crystal. Electrons in the conduction band are free electrons.



(a) Energy diagram (b) Bonding diagram

When an electron jumps to the conduction band, a vacancy is left in the valence band within the crystal. This vacancy is called a **hole**. For every electron raised to the conduction band by external energy, there is one hole left in the valence band, creating what is called an **electron-hole pair. Recombination** occurs when a conduction-band electron loses energy and falls back into a hole in the valence band.

To summarize, a piece of intrinsic silicon at room temperature has, at any instant, a number of conduction-band (free) electrons that are unattached to any atom and are essentially drifting randomly throughout the material. There is also an equal number of holes in the valence band created when these electrons jump into the conduction band. This is illustrated in Figure 1–14.

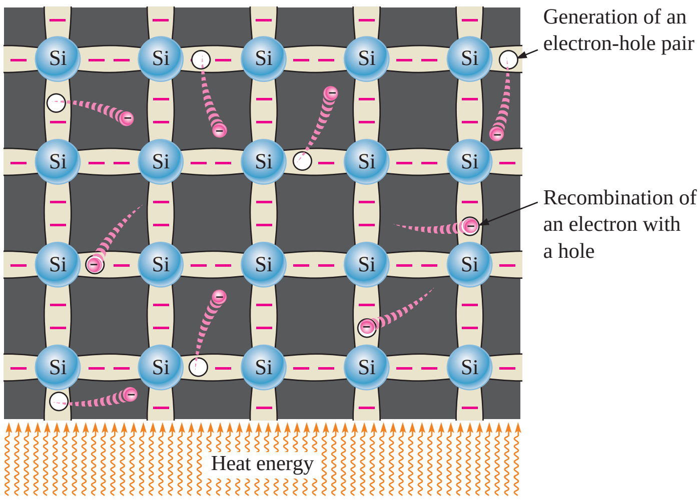


FIGURE 1–14

Electron-hole pairs in a silicon crystal. Free electrons are being generated continuously while some recombine with holes.

Electron and Hole Current

When a voltage is applied across a piece of intrinsic silicon, as shown in Figure 1-15, the thermally generated free electrons in the conduction band, which are free to move randomly in the crystal structure, are now easily attracted toward the positive end. This movement of free electrons is one type of **current** in a semiconductive material and is called *electron current.*

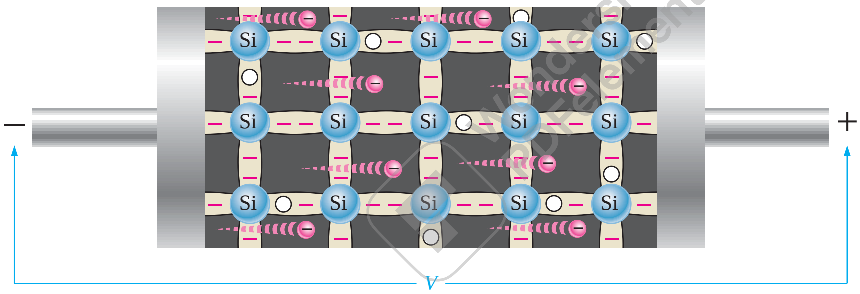


FIGURE 1–15

Electron current in intrinsic silicon is produced by the movement of thermally generated free electrons.

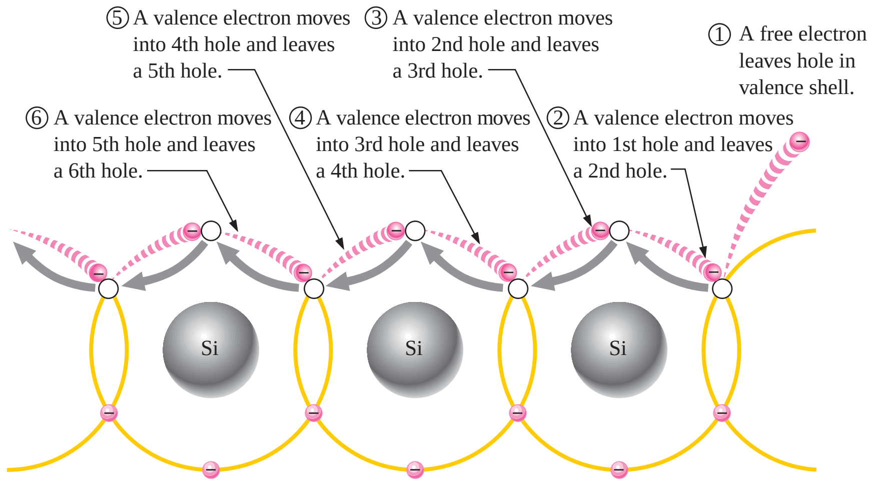
Another type of current occurs in the valence band, where the holes created by the free electrons exist. Electrons remaining in the valence band are still attached to their atoms and are not free to move randomly in the crystal structure as are the free electrons. However, a valence electron can move into a nearby hole with little change in its energy level, thus leaving another hole where it came from. Effectively the hole has moved from one place to another in the crystal structure, as illustrated in Figure 1–16. Although current in the valence band is produced by valence electrons, it is called *hole current* to distinguish it from electron current in the conduction band.

As you have seen, conduction in semiconductors is considered to be either the movement of free electrons in the conduction band or the movement of holes in the valence band, which is actually the movement of valence electrons to nearby atoms, creating hole current in the opposite direction.

It is interesting to contrast the two types of charge movement in a semiconductor with the charge movement in a metallic conductor, such as copper. Copper atoms form a different type of crystal in which the atoms are not covalently bonded to each other but consist of a “sea” of positive ion cores, which are atoms stripped of their valence electrons. The valence electrons are attracted to the positive ions, keeping the positive ions together and forming the metallic bond. The valence electrons do not belong to a given atom, but to the crystal as a whole. Since the valence electrons in copper are free to move, the application of a voltage results in current. There is only one type of current—the movement of free electrons—because there are no “holes” in the metallic crystal structure.

▶ FIGURE 1–16

Hole current in intrinsic silicon.



When a valence electron moves left to right to fill a hole while leaving another hole behind, the hole has effectively moved from right to left. Gray arrows indicate effective movement of a hole.

SECTION 1–3 CHECKUP

1. Are free electrons in the valence band or in the conduction band?
2. Which electrons are responsible for electron current in silicon?
3. What is a hole?
4. At what energy level does hole current occur?

1–4 *N*-TYPE AND *P*-TYPE SEMICONDUCTORS

Semiconductive materials do not conduct current well and are of limited value in their intrinsic state. This is because of the limited number of free electrons in the conduction band and holes in the valence band. Intrinsic silicon (or germanium) must be modified by increasing the number of free electrons or holes to increase its conductivity and make it useful in electronic devices. This is done by adding impurities to the intrinsic material. Two types of extrinsic (impure) semiconductive materials, *n*-type and *p*-type, are the key building blocks for most types of electronic devices.

After completing this section, you should be able to

- **Describe the properties of *n*-type and *p*-type semiconductors**
  - Define *doping*
- Explain how *n*-type semiconductors are formed
  - Describe a majority carrier and minority carrier in *n*-type material
- Explain how *p*-type semiconductors are formed
  - Describe a majority carrier and minority carrier in *p*-type material

Since semiconductors are generally poor conductors, their conductivity can be drastically increased by the controlled addition of impurities to the intrinsic (pure) semiconductive material. This process, called **doping**, increases the number of current carriers (electrons or holes). The two categories of impurities are *n*-type and *p*-type.

N-Type Semiconductor

To increase the number of conduction-band electrons in intrinsic silicon, **pentavalent** impurity atoms are added. These are atoms with five valence electrons such as arsenic (As), phosphorus (P), bismuth (Bi), and antimony (Sb).

As illustrated in Figure 1–17, each pentavalent atom (antimony, in this case) forms covalent bonds with four adjacent silicon atoms. Four of the antimony atom's valence electrons are used to form the covalent bonds with silicon atoms, leaving one extra electron. This extra electron becomes a conduction electron because it is not involved in bonding. Because the pentavalent atom gives up an electron, it is often called a *donor atom.* The number of conduction electrons can be carefully controlled by the number of impurity atoms added to the silicon. A conduction electron created by this doping process does not leave a hole in the valence band because it is in excess of the number required to fill the valence band.

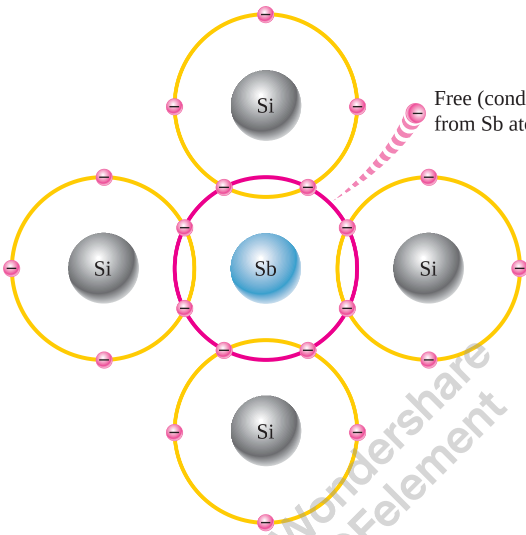


FIGURE 1–17

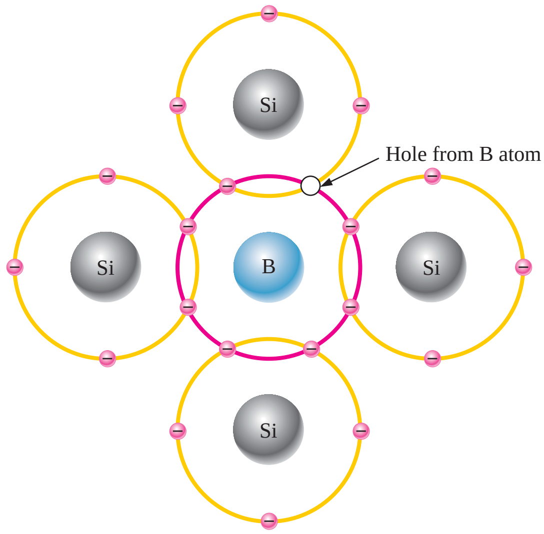
Pentavalent impurity atom in a silicon crystal structure. An antimony (Sb) impurity atom is shown in the center. The extra electron from the Sb atom becomes a free electron.

Majority and Minority Carriers Since most of the current carriers are electrons, silicon (or germanium) doped with pentavalent atoms is an *n*-type semiconductor (the *n* stands for the negative charge on an electron). The electrons are called the **majority carriers** in *n*-type material. Although the majority of current carriers in *n*-type material are electrons, there are also a few holes that are created when electron-hole pairs are thermally generated. These holes are *not* produced by the addition of the pentavalent impurity atoms. Holes in an *n*-type material are called **minority carriers.**

P-Type Semiconductor

To increase the number of holes in intrinsic silicon, **trivalent** impurity atoms are added. These are atoms with three valence electrons such as boron (B), indium (In), and gallium (Ga). As illustrated in Figure 1–18, each trivalent atom (boron, in this case) forms covalent bonds with four adjacent silicon atoms. All three of the boron atom's valence electrons are used in the covalent bonds; and, since four electrons are required, a hole results when each trivalent atom is added. Because the trivalent atom can take an electron, it is often referred to as an *acceptor atom.* The number of holes can be carefully controlled by the number of trivalent impurity atoms added to the silicon. A hole created by this doping process is *not* accompanied by a conduction (free) electron.

Majority and Minority Carriers Since most of the current carriers are holes, silicon (or germanium) doped with trivalent atoms is called a *p*-type semiconductor. The holes are the majority carriers in *p*-type material. Although the majority of current carriers in *p*-type material are holes, there are also a few conduction-band electrons that are created when electron-hole pairs are thermally generated. These conduction-band electrons are *not* produced by the addition of the trivalent impurity atoms. Conduction-band electrons in *p*-type material are the minority carriers.



▶ FIGURE 1–18

Trivalent impurity atom in a silicon crystal structure. A boron (B) impurity atom is shown in the center.

SECTION 1–4 CHECKUP

1. Define *doping.*
2. What is the difference between a pentavalent atom and a trivalent atom?
3. What are other names for the pentavalent and trivalent atoms?
4. How is an *n*-type semiconductor formed?
5. How is a *p*-type semiconductor formed?
6. What is the majority carrier in an *n*-type semiconductor?
7. What is the majority carrier in a *p*-type semiconductor?
8. By what process are the majority carriers produced?
9. By what process are the minority carriers produced?
10. What is the difference between intrinsic and extrinsic semiconductors?

1–5 THE *PN* JUNCTION

When you take a block of silicon and dope part of it with a trivalent impurity and the other part with a pentavalent impurity, a boundary called the *pn* junction is formed between the resulting *p*-type and *n*-type portions. The *pn* junction is the basis for diodes, certain transistors, solar cells, and other devices, as you will learn later.

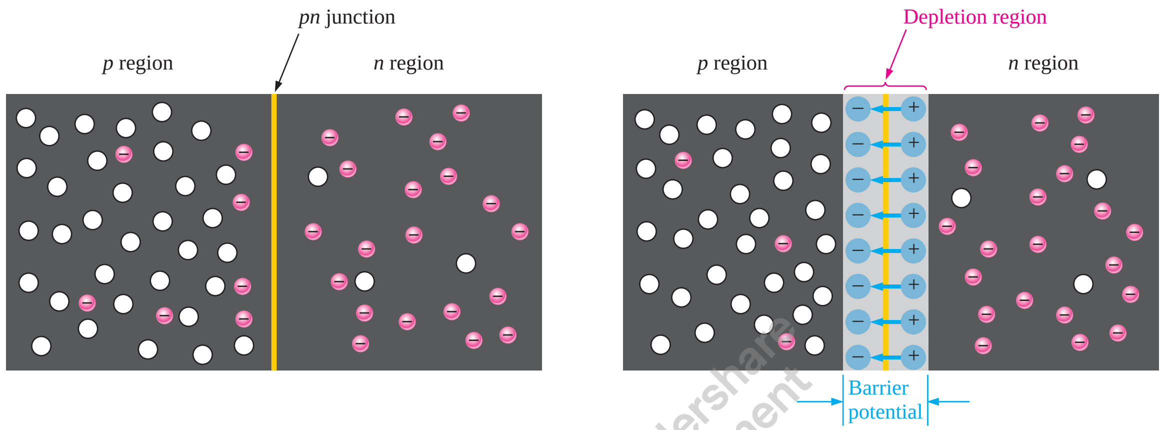
After completing this section, you should be able to

- **Describe how a *pn* junction is formed**
  - Discuss diffusion across a *pn* junction
- Explain the formation of the depletion region
  - Define *barrier potential* and discuss its significance ◆ State the values of barrier potential in silicon and germanium
- Discuss energy diagrams
  - Define *energy hill*

A *p*-type material consists of silicon atoms and trivalent impurity atoms such as boron. The boron atom adds a hole when it bonds with the silicon atoms. However, since the number of protons and the number of electrons are equal throughout the material, there is no net charge in the material and so it is neutral.

An *n*-type silicon material consists of silicon atoms and pentavalent impurity atoms such as antimony. As you have seen, an impurity atom releases an electron when it bonds with four silicon atoms. Since there is still an equal number of protons and electrons (including the free electrons) throughout the material, there is no net charge in the material and so it is neutral.

If a piece of intrinsic silicon is doped so that part is *n*-type and the other part is *p*-type, a ***pn* junction** forms at the boundary between the two regions and a diode is created, as indicated in Figure 1–19(a). The *p* region has many holes (majority carriers) from the impurity atoms and only a few thermally generated free electrons (minority carriers). The *n* region has many free electrons (majority carriers) from the impurity atoms and only a few thermally generated holes (minority carriers).



(a) The basic silicon structure at the instant of junction formation showing only the majority and minority carriers. Free electrons in the *n* region near the *pn* junction begin to diffuse across the junction and fall into holes near the junction in the *p* region.

(b) For every electron that diffuses across the junction and combines with a hole, a positive charge is left in the *n* region and a negative charge is created in the *p* region, forming a barrier potential. This action continues until the voltage of the barrier repels further diffusion. The blue arrows between the positive and negative charges in the depletion region represent the electric field.

▲ FIGURE 1–19

Formation of the depletion region. The width of the depletion region is exaggerated for illustration purposes.

Formation of the Depletion Region

The free electrons in the *n* region are randomly drifting in all directions. At the instant of the *pn* junction formation, the free electrons near the junction in the *n* region begin to diffuse across the junction into the *p* region where they combine with holes near the junction, as shown in Figure 1–19(b).

Before the *pn* junction is formed, recall that there are as many electrons as protons in the *n*-type material, making the material neutral in terms of net charge. The same is true for the *p*-type material.

When the *pn* junction is formed, the *n* region loses free electrons as they diffuse across the junction. This creates a layer of positive charges (pentavalent ions) near the junction. As the electrons move across the junction, the *p* region loses holes as the electrons and holes combine. This creates a layer of negative charges (trivalent ions) near the junction. These two layers of positive and negative charges form the **depletion region,** as shown in Figure 1–19(b). The term *depletion* refers to the fact that the region near the *pn* junction is depleted of charge carriers (electrons and holes) due to diffusion across the junction. Keep in mind that the depletion region is formed very quickly and is very thin compared to the *n* region and *p* region.

After the initial surge of free electrons across the *pn* junction, the depletion region has expanded to a point where equilibrium is established and there is no further diffusion of

HISTORY NOTE

After the invention of the light bulb, Edison continued to experiment and in 1883 found that he could detect electrons flowing through the vacuum from the lighted filament to a metal plate mounted inside the bulb. This discovery became known as the *Edison effect.*

An English physicist, John Fleming, took up where Edison left off and found that the Edison effect could also be used to detect radio waves and convert them to electrical signals. He went on to develop a two-element vacuum tube called the *Fleming valve,* later known as the *diode.* Modern *pn* junction devices are an outgrowth of this.

HISTORY NOTE

Russell Ohl, working at Bell Labs in 1940, stumbled on the semiconductor *pn* junction. Ohl was working with a silicon sample that had an accidental crack down its middle. He was using an ohmmeter to test the electrical resistance of the sample when he noted that when the sample was exposed to light, the current that flowed between the two sides of the crack made a significant jump. This discovery was fundamental to the work of the team that invented the transistor in 1947.

electrons across the junction. This occurs as follows. As electrons continue to diffuse across the junction, more and more positive and negative charges are created near the junction as the depletion region is formed. A point is reached where the total negative charge in the depletion region repels any further diffusion of electrons (negatively charged particles) into the *p* region (like charges repel) and the diffusion stops. In other words, the depletion region acts as a barrier to the further movement of electrons across the junction.

Barrier Potential Any time there is a positive charge and a negative charge near each other, there is a force acting on the charges as described by Coulomb's law. In the depletion region there are many positive charges and many negative charges on opposite sides of the *pn* junction. The forces between the opposite charges form an *electric field*, as illustrated in Figure 1–19(b) by the blue arrows between the positive charges and the negative charges. This electric field is a barrier to the free electrons in the *n* region, and energy must be expended to move an electron through the electric field. That is, external energy must be applied to get the electrons to move across the barrier of the electric field in the depletion region.

The potential difference of the electric field across the depletion region is the amount of voltage required to move electrons through the electric field. This potential difference is called the **barrier potential** and is expressed in volts. Stated another way, a certain amount of voltage equal to the barrier potential and with the proper polarity must be applied across a *pn* junction before electrons will begin to flow across the junction. You will learn more about this when we discuss *biasing* in Chapter 2.

The barrier potential of a *pn* junction depends on several factors, including the type of semiconductive material, the amount of doping, and the temperature. The typical barrier potential is approximately 0.7 V for silicon and 0.3 V for germanium at 25°C. Because germanium devices are not widely used, silicon will be used throughout the rest of the book.

Energy Diagrams of the *PN* Junction and Depletion Region

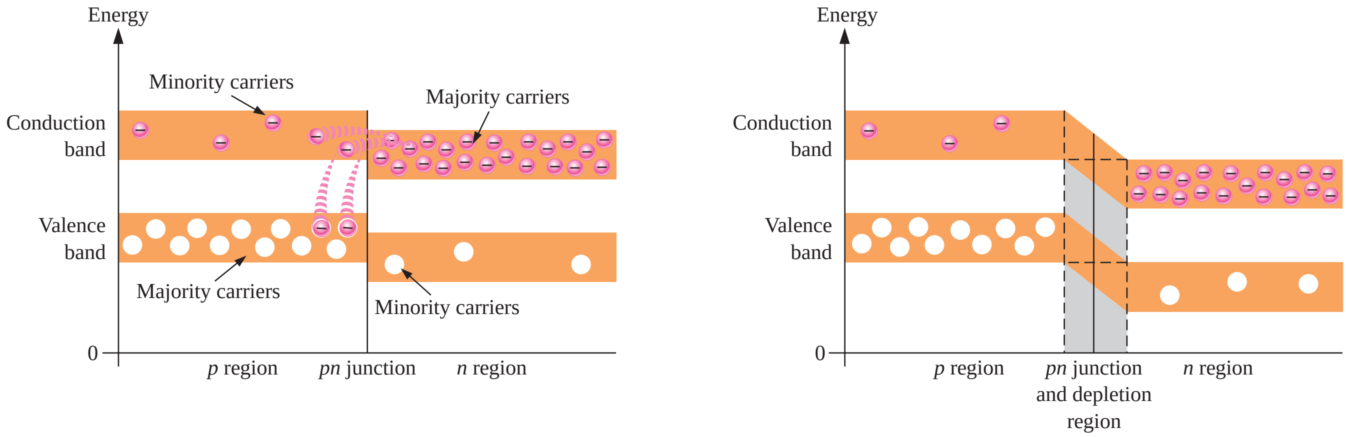
The valence and conduction bands in an *n*-type material are at slightly lower energy levels than the valence and conduction bands in a *p*-type material. Recall that *p*-type material has trivalent impurities and *n*-type material has pentavalent impurities. The trivalent impurities exert lower forces on the outer-shell electrons than the pentavalent impurities. The lower forces in *p*-type materials mean that the electron orbits are slightly larger and hence have greater energy than the electron orbits in the *n*-type materials.

An energy diagram for a *pn* junction at the instant of formation is shown in Figure 1–20(a). As you can see, the valence and conduction bands in the *n* region are at lower energy levels than those in the *p* region, but there is a significant amount of overlapping.

The free electrons in the *n* region that occupy the upper part of the conduction band in terms of their energy can easily diffuse across the junction (they do not have to gain additional energy) and temporarily become free electrons in the lower part of the *p*-region conduction band. After crossing the junction, the electrons quickly lose energy and fall into the holes in the *p*-region valence band as indicated in Figure 1-20(a).

As the diffusion continues, the depletion region begins to form and the energy level of the *n*-region conduction band decreases. The decrease in the energy level of the conduction band in the *n* region is due to the loss of the higher-energy electrons that have diffused across the junction to the *p* region. Soon, there are no electrons left in the *n*-region conduction band with enough energy to get across the junction to the *p*-region conduction band, as indicated by the alignment of the top of the *n*-region conduction band and the bottom of the *p*-region conduction band in Figure 1–20(b). At this point, the junction is at equilibrium; and the depletion region is complete because diffusion has ceased. There is an energy gradiant across the depletion region which acts as an "energy hill" that an *n*-region electron must climb to get to the *p* region.

Notice that as the energy level of the *n*-region conduction band has shifted downward, the energy level of the valence band has also shifted downward. It still takes the same amount of energy for a valence electron to become a free electron. In other words, the energy gap between the valence band and the conduction band remains the same.



(a) At the instant of junction formation

(b) At equilibrium

▲ **FIGURE 1–20**

Energy diagrams illustrating the formation of the *pn* junction and depletion region.

SECTION 1–5 CHECKUP

1. What is a *pn* junction?
2. Explain diffusion.
3. Describe the depletion region.
4. Explain what the barrier potential is and how it is created.
5. What is the typical value of the barrier potential for a silicon diode?
6. What is the typical value of the barrier potential for a germanium diode?

SUMMARY

Section 1–1

- According to the classical Bohr model, the atom is viewed as having a planetary-type structure with electrons orbiting at various distances around the central nucleus.
- According to the quantum model, electrons do not exist in precise circular orbits as particles as in the Bohr model. The electrons can be waves or particles and precise location at any time is uncertain.
- The nucleus of an atom consists of protons and neutrons. The protons have a positive charge and the neutrons are uncharged. The number of protons is the atomic number of the atom.
- Electrons have a negative charge and orbit around the nucleus at distances that depend on their energy level. An atom has discrete bands of energy called *shells* in which the electrons orbit. Atomic structure allows a certain maximum number of electrons in each shell. In their natural state, all atoms are neutral because they have an equal number of protons and electrons.
- The outermost shell or band of an atom is called the *valence band*, and electrons that orbit in this band are called *valence electrons.* These electrons have the highest energy of all those in the atom. If a valence electron acquires enough energy from an outside source such as heat, it can jump out of the valence band and break away from its atom.

Section 1–2

- Insulating materials have very few free electrons and do not conduct current at all under normal circumstances.
- Materials that are conductors have a large number of free electrons and conduct current very well.
- Semiconductive materials fall in between conductors and insulators in their ability to conduct current.
- Semiconductor atoms have four valence electrons. Silicon is the most widely used semiconductive material.

- Semiconductor atoms bond together in a symmetrical pattern to form a solid material called a *crystal.* The bonds that hold a crystal together are called *covalent bonds.*

Section 1–3

- The valence electrons that manage to escape from their parent atom are called *conduction electrons* or *free electrons.* They have more energy than the electrons in the valence band and are free to drift throughout the material.
- When an electron breaks away to become free, it leaves a hole in the valence band creating what is called an *electron-hole pair.* These electron-hole pairs are thermally produced because the electron has acquired enough energy from external heat to break away from its atom.
- A free electron will eventually lose energy and fall back into a hole. This is called *recombination.* Electron-hole pairs are continuously being thermally generated so there are always free electrons in the material.
- When a voltage is applied across the semiconductor, the thermally produced free electrons move toward the positive end and form the current. This is one type of current and is called electron current.
- Another type of current is the hole current. This occurs as valence electrons move from hole to hole creating, in effect, a movement of holes in the opposite direction.

Section 1–4

- An *n*-type semiconductive material is created by adding impurity atoms that have five valence electrons. These impurities are *pentavalent atoms.* A *p*-type semiconductor is created by adding impurity atoms with only three valence electrons. These impurities are *trivalent atoms.*
- The process of adding pentavalent or trivalent impurities to a semiconductor is called *doping.*
- The majority carriers in an *n*-type semiconductor are free electrons acquired by the doping process, and the minority carriers are holes produced by thermally generated electron-hole pairs. The majority carriers in a *p*-type semiconductor are holes acquired by the doping process, and the minority carriers are free electrons produced by thermally generated electron-hole pairs.

Section 1–5

- A *pn* junction is formed when part of a material is doped *n*-type and part of it is doped *p*-type. A depletion region forms starting at the junction that is devoid of any majority carriers. The depletion region is formed by ionization.
- The barrier potential is typically 0.7 V for a silicon diode and 0.3 V for germanium.

KEY TERMS

Key terms and other bold terms are defined in the end-of-book glossary.

Atom The smallest particle of an element that possesses the unique characteristics of that element.

Barrier potential The amount of energy required to produce full conduction across the *pn* junction in forward bias.

Conductor A material that easily conducts electrical current.

Crystal A solid material in which the atoms are arranged in a symmetrical pattern.

Doping The process of imparting impurities to an intrinsic semiconductive material in order to control its conduction characteristics.

Electron The basic particle of negative electrical charge.

Free electron An electron that has acquired enough energy to break away from the valence band of the parent atom; also called a *conduction electron.*

Hole The absence of an electron in the valence band of an atom.

Insulator A material that does not normally conduct current.

Ionization The removal or addition of an electron from or to a neutral atom so that the resulting atom (called an ion) has a net positive or negative charge.

Orbital Subshell in the quantum model of an atom.

***PN* junction** The boundary between two different types of semiconductive materials.

Proton The basic particle of positive charge.

Semiconductor A material that lies between conductors and insulators in its conductive properties. Silicon, germanium, and carbon are examples.

Shell An energy band in which electrons orbit the nucleus of an atom.

Silicon A semiconductive material.

Valence Related to the outer shell of an atom.

KEY FORMULA

1–1 $N_e = 2n^2$ Maximum number of electrons in any shell

TRUE/FALSE QUIZ

Answers can be found at www.pearsonhighered.com/floyd.

1. An atom is the smallest particle in an element.
2. An electron is a negatively charged particle.
3. An atom is made up of electrons, protons, and neutrons.
4. Electrons are part of the nucleus of an atom.
5. Valence electrons exist in the outer shell of an atom.
6. Crystals are formed by the bonding of atoms.
7. Silicon is a conductive material.
8. Silicon doped with *p* and *n* impurities has one *pn* junction.
9. The *p* and *n* regions are formed by a process called *ionization*.

SELF-TEST

Answers can be found at www.pearsonhighered.com/floyd.

Section 1–1

1. Every known element has
   (a) the same type of atoms **(b)** the same number of atoms
   (c) a unique type of atom **(d)** several different types of atoms
2. An atom consists of
   (a) one nucleus and only one electron **(b)** one nucleus and one or more electrons
   (c) protons, electrons, and neutrons **(d)** answers (b) and (c)
3. The nucleus of an atom is made up of
   (a) protons and neutrons **(b)** electrons
   (c) electrons and protons **(d)** electrons and neutrons
4. Valence electrons are
   (a) in the closest orbit to the nucleus **(b)** in the most distant orbit from the nucleus
   (c) in various orbits around the nucleus **(d)** not associated with a particular atom
5. A positive ion is formed when
   (a) a valence electron breaks away from the atom
   (b) there are more holes than electrons in the outer orbit
   (c) two atoms bond together
   (d) an atom gains an extra valence electron

Section 1–2

6. The most widely used semiconductive material in electronic devices is
   (a) germanium **(b)** carbon **(c)** copper **(d)** silicon
7. The difference between an insulator and a semiconductor is
   (a) a wider energy gap between the valence band and the conduction band
   (b) the number of free electrons
   (c) the atomic structure
   (d) answers (a), (b), and (c)
8. The energy band in which free electrons exist is the
   (a) first band **(b)** second band **(c)** conduction band **(d)** valence band

9. In a semiconductor crystal, the atoms are held together by
   (a) the interaction of valence electrons (b) forces of attraction
   (c) covalent bonds (d) answers (a), (b), and (c)
10. The atomic number of silicon is
    (a) 8 (b) 2 (c) 4 (d) 14
11. The atomic number of germanium is
    (a) 8 (b) 2 (c) 4 (d) 32
12. The valence shell in a silicon atom has the number designation of
    (a) 0 (b) 1 (c) 2 (d) 3
13. Each atom in a silicon crystal has
    (a) four valence electrons
    (b) four conduction electrons
    (c) eight valence electrons, four of its own and four shared
    (d) no valence electrons because all are shared with other atoms

Section 1–3

14. Electron-hole pairs are produced by
    (a) recombination (b) thermal energy (c) ionization (d) doping
15. Recombination is when
    (a) an electron falls into a hole
    (b) a positive and a negative ion bond together
    (c) a valence electron becomes a conduction electron
    (d) a crystal is formed
16. The current in a semiconductor is produced by
    (a) electrons only (b) holes only (c) negative ions (d) both electrons and holes

Section 1–4

17. In an intrinsic semiconductor,
    (a) there are no free electrons
    (b) the free electrons are thermally produced
    (c) there are only holes
    (d) there are as many electrons as there are holes
    (e) answers (b) and (d)
18. The process of adding an impurity to an intrinsic semiconductor is called
    (a) doping (b) recombination (c) atomic modification (d) ionization
19. A trivalent impurity is added to silicon to create
    (a) germanium (b) a *p*-type semiconductor
    (c) an *n*-type semiconductor (d) a depletion region
20. The purpose of a pentavalent impurity is to
    (a) reduce the conductivity of silicon (b) increase the number of holes
    (c) increase the number of free electrons (d) create minority carriers
21. The majority carriers in an *n*-type semiconductor are
    (a) holes (b) valence electrons (c) conduction electrons (d) protons
22. Holes in an *n*-type semiconductor are
    (a) minority carriers that are thermally produced
    (b) minority carriers that are produced by doping
    (c) majority carriers that are thermally produced
    (d) majority carriers that are produced by doping

Section 1–5

23. A *pn* junction is formed by
    (a) the recombination of electrons and holes
    (b) ionization

(c) the boundary of a *p*-type and an *n*-type material
(d) the collision of a proton and a neutron

24. The depletion region is created by
(a) ionization (b) diffusion (c) recombination (d) answers (a), (b), and (c)

25. The depletion region consists of
(a) nothing but minority carriers (b) positive and negative ions
(c) no majority carriers (d) answers (b) and (c)

PROBLEMS

Answers to all odd-numbered problems are at the end of the book.

BASIC PROBLEMS

Section 1–1 The Atom

1. If the atomic number of a neutral atom is 6, how many electrons does the atom have? How many protons?
2. What is the maximum number of electrons that can exist in the 3rd shell of an atom?

Section 1–2 Materials Used in Electronics

3. For each of the energy diagrams in Figure 1–21, determine the class of material based on relative comparisons.
4. A certain atom has four valence electrons. What type of atom is it?
5. In a silicon crystal, how many covalent bonds does a single atom form?

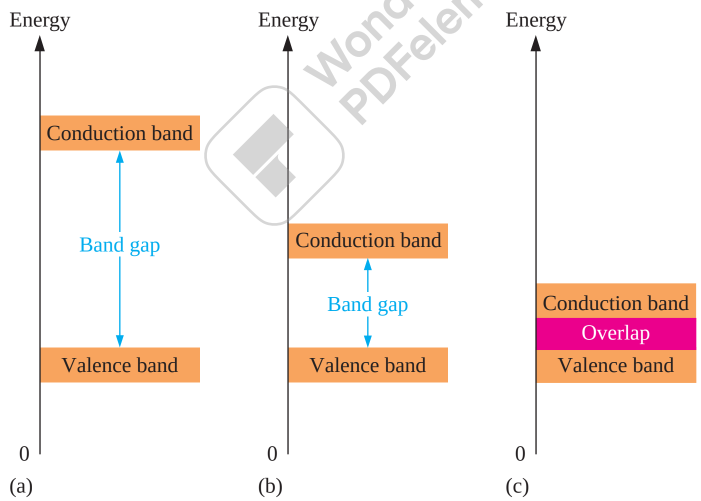


FIGURE 1–21

Section 1–3 Current in Semiconductors

6. What happens when heat is added to silicon?
7. Name the two energy bands at which current is produced in silicon.

Section 1–4 *N*-Type and *P*-Type Semiconductors

8. Describe the process of doping and explain how it alters the atomic structure of silicon.
9. What is antimony? What is boron?

Section 1–5 The *PN* Junction

10. How is the electric field across the *pn* junction created?
11. Because of its barrier potential, can a diode be used as a voltage source? Explain.

GreenTech Application 1: *Solar Power*

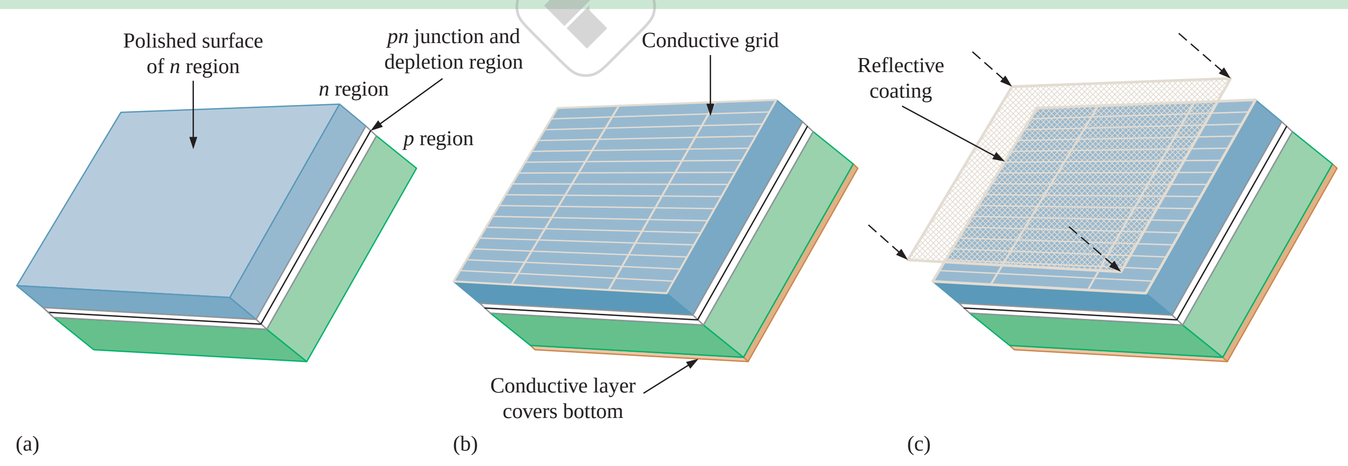
Photovoltaic (PV) Cell Structure and Operation

The key feature of a PV (solar) cell is the *pn* junction that was covered in Chapter 1. The **photovoltaic effect** is the basic physical process by which a solar cell converts sunlight into electricity. Sunlight contains photons or "packets" of energy sufficient to create electron-hole pairs in the *n* and *p* regions. Electrons accumulate in the *n*-region and holes accumulate in the *p* region, producing a potential difference (voltage) across the cell. When an external load is connected, the electrons flow through the semiconductor material and provide current to the external load.

The Solar Cell Structure Although there are other types of solar cells and continuing research promises new developments in the future, the crystalline silicon solar cell is by far the most widely used. A silicon solar cell consists of a thin layer or wafer of silicon that has been doped to create a *pn* junction. The depth and distribution of impurity atoms can be controlled very precisely during the doping process. The most commonly used process for creating a silicon ingot, from which a silicon wafer is cut, is called the *Czochralski method*. In this process, a seed crystal of silicon is dipped into melted polycrystalline silicon. As the seed crystal is withdrawn and rotated, a cylindrical ingot of silicon is formed.

Thin circular shaped-wafers are sliced from an ingot of ultra-pure silicon and then are polished and trimmed to an octagonal, hexagonal, or rectangular shape for maximum coverage when fitted into an array. The silicon wafer is doped so that the *n* region is much thinner than the *p* region to permit light penetration, as shown in Figure GA1–1(a).

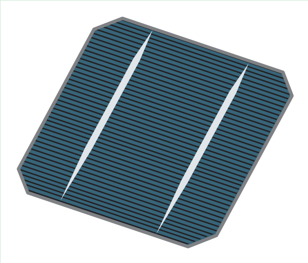
A grid-work of very thin conductive contact strips are deposited on top of the wafer by methods such as photoresist or silk-screen, as shown in part (b). The contact grid must maximize the surface area of the silicon wafer that be exposed to the sunlight in order to collect as much light energy as possible.



▲ **FIGURE GA1–1**

Basic construction of a PV solar cell.

The conductive grid across the top of the cell is necessary so that the electrons have a shorter distance to travel through the silicon when an external load is connected. The farther electrons travel through the silicon material, the greater the energy loss due to resistance. A solid contact covering all of the bottom of the wafer is then added, as indicated in the figure. Thickness of the solar cell compared to the surface area is greatly exaggerated for purposes of illustration.



▲ FIGURE GA1–2

A complete PV solar cell.

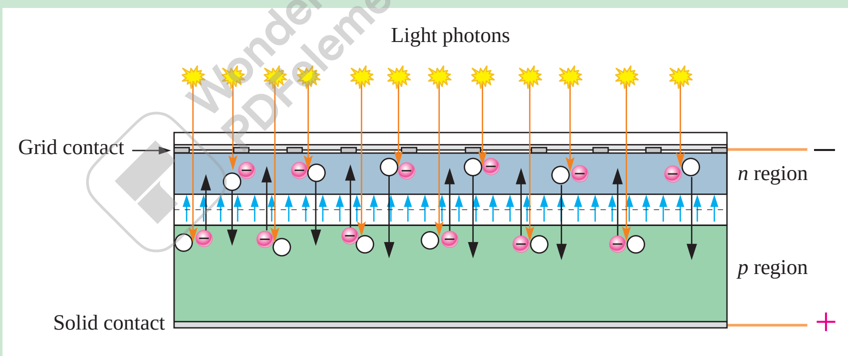
After the contacts are incorporated, an antireflective coating is placed on top the contact grid and *n* region, as shown in Figure GA1–1(c). This allows the solar cell to absorb as much of the sun's energy as possible by reducing the amount of light energy reflected away from the surface of the cell. Finally, a glass or transparent plastic layer is attached to the top of the cell with transparent adhesive to protect it from the weather. Figure GA1–2 shows a completed solar cell.

Operation of a Solar Cell As indicated before, sunlight is composed of photons, or "packets" of energy. The sun produces an astounding amount of energy. The small fraction of the sun's total energy that reaches the earth is enough to meet all of our power needs many times over. There is sufficient solar energy striking the earth each hour to meet worldwide demands for an entire year.

The *n*-type layer is very thin compared to the *p* region to allow light penetration into the *p* region. The thickness of the entire cell is actually about the thickness of an eggshell. When a photon penetrates either the *n* region or the *p*-type region and strikes a silicon atom near the *pn* junction with sufficient energy to knock an electron out of the valence band, the electron becomes a free electron and leaves a hole in the valence band, creating an *electron-hole pair.* The amount of energy required to free an electron from the valence band of a silicon atom is called the band-gap energy and is 1.12 eV (electron volts). In the *p* region, the free electron is swept across the depletion region by the electric field into the *n* region. In the *n* region, the hole is swept across the depletion region by the electric field into the *p* region. Electrons accumulate in the *n* region, creating a negative charge; and holes accumulate in the *p* region, creating a positive charge. A voltage is developed between the *n* region and *p* region contacts, as shown in Figure GA1–3.

▶ FIGURE GA1–3

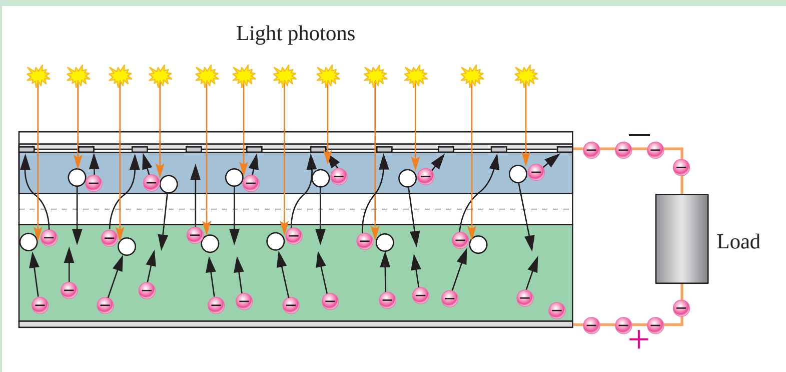
Basic operation of a solar cell with incident sunlight.



When a load is connected to a solar cell via the top and bottom contacts, the free electrons flow out of the *n* region to the grid contacts on the top surface, through the negative contact, through the load and back into the positive contact on the bottom surface, and into the *p* region where they can recombine with holes. The sunlight energy continues to create new electron-hole pairs and the process goes on, as illustrated in Figure GA1–4.

▶ FIGURE GA1–4

A solar cell producing voltage and current through a load under incident sunlight.



Solar Cell Characteristics

Solar cells are typically 100 cm^2 to 225 cm^2 in size. The usable voltage from silicon solar cells is approximately 0.5 V to 0.6 V. Terminal voltage is only slightly dependent on the intensity of light radiation, but the current increases with light intensity. For example, a 100 cm^2 silicon cell reaches a maximum current of approximately 2 A when radiated by 1000 W/m^2 of light.

Figure GA1–5 shows the *V-I* characteristic curves for a typical solar cell for various light intensities. Higher light intensity produces more current. The operating point for maximum power output for a given light intensity should be in the “knee” area of the curve, as indicated by the dashed line. The load on the solar cell controls this operating point ($R_L = V/I$).

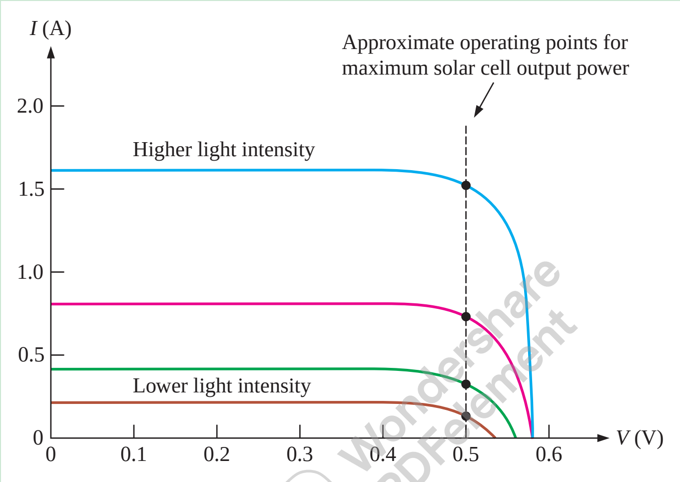


FIGURE GA1–5 *V-I* characteristic for a typical single solar cell from increasing light intensities.

In a solar power system, the cell is generally loaded by a charge controller or an inverter. A special method called *maximum power point tracking* will sense the operating point and adjust the load resistance to keep it in the knee region. For example, assume the solar cell is operating on the highest intensity curve (blue) shown in Figure GA1–5. For maximum power (dashed line), the voltage is 0.5 V and the current is 1.5 A. For this condition, the load is

$$R_L = \frac{V}{I} = \frac{0.5\text{ V}}{1.5\text{ A}} = 0.33\ \Omega$$

Now, if the light intensity falls to where the cell is operating on the red curve, the current is less and the load resistance will have to change to maintain maximum power output as follows:

$$R_L = \frac{V}{I} = \frac{0.5\text{ V}}{0.8\text{ A}} = 0.625\ \Omega$$

If the resistance did not change, the voltage output would drop to

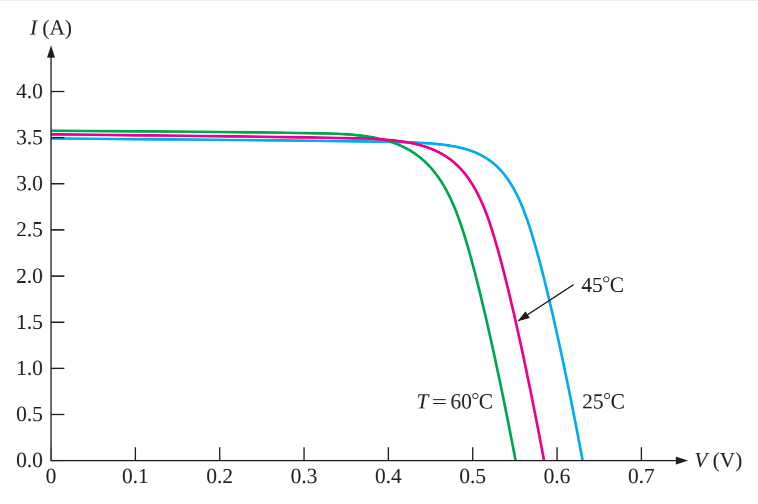
$$V = IR = (0.8\text{ A})(0.33\text{ W}) = 0.264\text{ V}$$

resulting in less than maximum power output for the red curve. Of course, the power will still be less on the red curve than on the blue curve because the current is less.

The output voltage and current of a solar cell is also temperature dependent. Notice in Figure GA1–6 that for a constant light intensity the output voltage decreases as the temperature increases but the current is affected only by a small amount.

▶ FIGURE GA1–6

Effect of temperature on output voltage and current for a fixed light intensity in a solar cell.



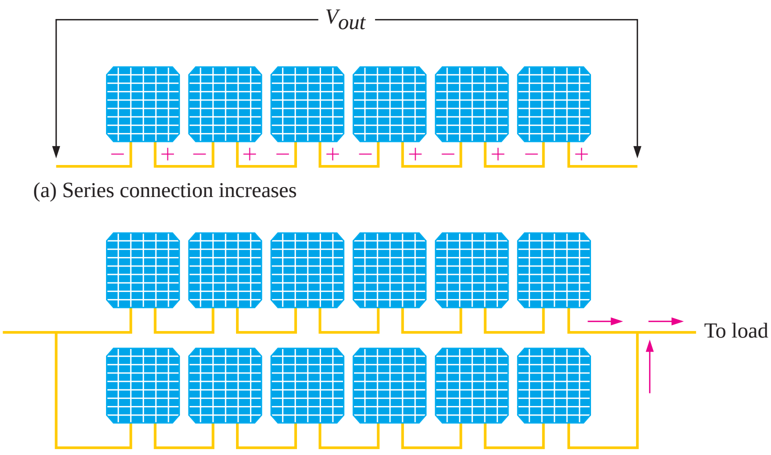
Solar Cell Panels

Currently, the problem is in harnessing solar energy in sufficient amounts and at a reasonable cost to meet our requirements. It takes approximately a square meter solar panel to produce 100 W in a sunny climate. Some energy can be harvested even if cloud cover exists, but no energy can be obtained during the night.

A single solar cell is impractical for most applications because it can produce only about 0.5 V to 0.6 V. To produce higher voltages, multiple solar cells are connected in series as shown in Figure GA1–7(a). For example, the six series cells will ideally produce 6(0.5 V) = 3 V. Since they are connected in series, the six cells will produce the same current as a single cell. For increased current capacity, series cells are connected in parallel, as shown in part (b). Assuming a cell can produce 2 A, the series-parallel arrangement of twelve cells will produce 4 A at 3 V. Multiple cells connected to produce a specified power output are called *solar panels* or *solar modules.*

▶ FIGURE GA1–7

Solar cells connected together to create an array called a solar panel.



(a) Series connection increases

(b) Series-parallel connection increases current

Solar panels are generally available in 12 V, 24 V, 36 V, and 48 V versions. Higher output solar panels are also available for special applications. In actuality, a 12 V solar panel produces more than 12 V (15 V to 20 V) in order to charge a 12 V battery and compensate for voltage drops in the series connection and other losses. Ideally, a panel with 24 individual solar cells is required to produce an output of 12 V, assuming each cell produces 0.5 V. In practice, more than thirty cells are typically used in a 12 V panel. Manufacturers usually specify the output of a solar panel in terms of power at a certain solar radiation called the *peak sun irradiance* which is 1000 W/m^2. For example, a 12 V solar panel that has a rated voltage of 17 V and produces a current of 3.5 A to a load at peak sun condition has a specified output power of

$$P = VI = (17\text{ V})(3.5\text{ A}) = 59.5\text{ W}$$

Many solar panels can be interconnected to form large arrays for high power outputs, as illustrated in Figure GA1–8.

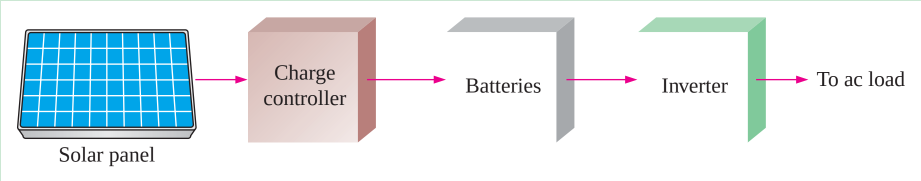
▲ FIGURE GA1–8

Large array of solar panels.

The Solar Power System

A basic solar power system that can supply power to ac loads generally consists of four components, as shown in the block diagram in Figure GA1-9. These components are the solar panel, the charge controller, the batteries, and the inverter. For supplying only dc loads, such as solar-powered instruments and dc lamps, the inverter is not needed. Some solar power systems do not include battery backup or the charge controller and are used to provide supplemental power only when the sun is shining.

Efficiency is an important characteristic of a solar power system. Energy loss due to voltage drops, the photovoltaic process, and other factors are inevitable, so minimizing losses is a critical consideration in solar power systems.



◀ FIGURE GA1–9

Basic solar power system with battery backup.

Solar Panel The solar panel collects energy from the sun and converts it to electrical energy through the photovoltaic process. Of course, the solar panel will not produce the specified power output all of the time. For example, if there is 4 hours of peak sun during a given day, a 60 W panel will produce $4 \times 60\text{ W} = 240\text{ Wh}$ of energy. For the hours that the sun is not peak, the output will depend on the percentage of peak sun and is less than the specified output. A system is typically designed taking into account the annual of average peak sun per day for a given geographical area.

Charge Controller A charge controller, also called a charge regulator, takes the output of the solar panel and ensures that the battery is charged efficiently and is not overcharged. Generally, the charge controller is rated based on the amount of current it can regulate. The operation of many solar charge controllers is based on the principle of *pulse-width modulation.* Also, some controllers include a charging method that maximizes charging, called maximum power point tracking. The charge controller and batteries in a solar power system will be examined in more detail in GreenTech Application 2.

Battery Deep-cycle batteries, such as lead-acid, are used in solar power systems because they can be charged and discharged hundreds or thousands of times. Recall that batteries are rated in ampere-hours (Ah), which specifies the current that can be supplied for certain number of hours. For example, a 400 Ah battery can supply 400 A for one hour, 4 A for 100 hours, or 10 A for 40 hours. Batteries can be connected in series to increase voltage or in parallel to increase amp-hrs.

Inverter The inverter changes DC voltage stored in the battery to the standard 120/240 Vac used in most common applications such as lighting, appliances, and motors. Basically, in an inverter the dc from the battery is electronically switched on and off and filtered to produce a sinusoidal ac output. The ac output is then applied to a step-up transformer to get 120 Vac. The inverter in a solar system will be covered in more detail in GreenTech Application 3.

Questions

Some questions may require research beyond the content of this coverage. Answers can be found at www.pearsonhighered.com/floyd.

1. What are the four elements of a solar power system?
2. How must solar cells be connected to increase output voltage?
3. What is the function of the charge controller?
4. What is the function of the inverter?
5. What range of solar panels in terms of output voltage and power are available?

The following websites are recommended for viewing solar cells in action. Many other websites are also available. Note that websites can occasionally be removed and are not guaranteed to be available.

http://www.youtube.com/watch?v=hdUdu5C8Tis&feature=related

http://www.youtube.com/watch?v=Caf1Jlz4X2l

http://www.youtube.com/watch?v=K76r41jaGJg&feature=related

http://www.youtube.com/watch?v=2mCTSV2f36A&feature=related

http://www.youtube.com/watch?v=PbPcmo3x1Ug&feature=related

2 Diodes and Applications

Chapter Outline

2–1 Diode Operation
2–2 Voltage-Current (*V-I*) Characteristics of a Diode
2–3 Diode Models
2–4 Half-Wave Rectifiers
2–5 Full-Wave Rectifiers
2–6 Power Supply Filters and Regulators
2–7 Diode Limiters and Clampers
2–8 Voltage Multipliers
2–9 The Diode Datasheet
2–10 Troubleshooting
Application Activity
GreenTech Application 2: *Solar Power*

Chapter Objectives

- Use a diode in common applications
- Analyze the voltage-current (*V-I*) characteristic of a diode
- Explain how the three diode models differ
- Explain and analyze the operation of half-wave rectifiers
- Explain and analyze the operation of full-wave rectifiers
- Explain and analyze power supply filters and regulators
- Explain and analyze the operation of diode limiters and clampers
- Explain and analyze the operation of diode voltage multipliers
- Interpret and use diode datasheets
- Troubleshoot diodes and power supply circuits

Key Terms

- Diode
- Bias
- Forward bias
- Reverse bias
- *V-I* characteristic
- DC power supply
- Rectifier
- Filter
- Regulator
- Half-wave rectifier
- Peak inverse voltage (PIV)
- Full-wave rectifier
- Ripple voltage
- Line regulation
- Load regulation
- Limiter
- Clamper
- Troubleshooting

Visit the Companion Website

Study aids and Multisim files for this chapter are available at http://www.pearsonhighered.com/electronics

Introduction

In Chapter 1, you learned that many semiconductor devices are based on the *pn* junction. In this chapter, the operation and characteristics of the diode are covered. Also, three diode models representing three levels of approximation are presented and testing is discussed. The importance of the diode in electronic circuits cannot be overemphasized. Its ability to conduct current in one direction while blocking current in the other direction is essential to the operation of many types of circuits. One circuit in particular is the ac rectifier, which is covered in this chapter. Other important applications are circuits such as diode limiters, diode clampers, and diode voltage multipliers. A datasheet is discussed for specific diodes.

Application Activity Preview

You have the responsibility for the final design and testing of a power supply circuit that your company plans to use in several of its products. You will apply your knowledge of diode circuits to the Application Activity at the end of the chapter.

2–1 DIODE OPERATION

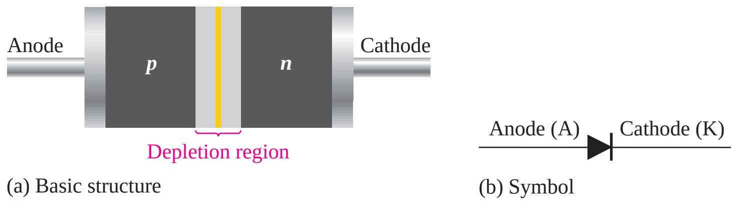
Similar to the solar cell in Chapter 1, a diode is a two-terminal semiconductor device formed by two doped regions of silicon separated by a *pn* junction. In this chapter, the most common category of diode, known as the general-purpose diode, is covered. Other names, such as rectifier diode or signal diode, depend on the particular type of application for which the diode was designed. You will learn how to use a voltage to cause the diode to conduct current in one direction and block it in the other direction. This process is called *biasing*.

After completing this section, you should be able to

- **Use a diode in common applications**
- Recognize the electrical symbol for a diode and several diode package configurations
- Apply forward bias to a diode
  ◆ Define *forward bias* and state the required conditions ◆ Discuss the effect of forward bias on the depletion region ◆ Define *barrier potential* and its effects during forward bias
- Reverse-bias a diode
  ◆ Define *reverse bias* and state the required conditions ◆ Discuss reverse current and reverse breakdown

The Diode

As mentioned, a **diode** is made from a small piece of semiconductor material, usually silicon, in which half is doped as a *p* region and half is doped as an *n* region with a *pn* junction and depletion region in between. The *p* region is called the **anode** and is connected to a conductive terminal. The *n* region is called the **cathode** and is connected to a second conductive terminal. The basic diode structure and schematic symbol are shown in Figure 2–1.



◄ FIGURE 2–1

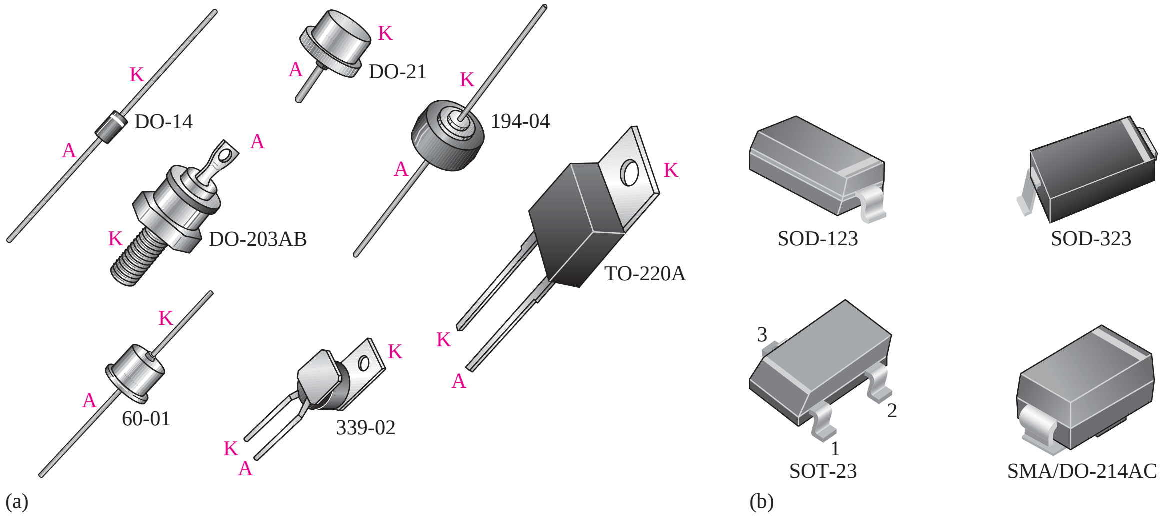
The diode.

Typical Diode Packages Several common physical configurations of through-hole mounted diodes are illustrated in Figure 2–2(a). The anode (A) and cathode (K) are indicated on a diode in several ways, depending on the type of package. The cathode is usually marked by a band, a tab, or some other feature. On those packages where one lead is connected to the case, the case is the cathode.

Surface-Mount Diode Packages Figure 2–2(b) shows typical diode packages for surface mounting on a printed circuit board. The SOD and SOT packages have gull-wing shaped leads. The SMA package has L-shaped leads that bend under the package. The SOD and SMA types have a band on one end to indicate the cathode. The SOT type is a three-terminal package in which there are either one or two diodes. In a single-diode SOT package, pin 1 is usually the anode and pin 3 is the cathode. In a dual-diode SOT package, pin 3 is the common terminal and can be either the anode or the cathode. Always check the datasheet for the particular diode to verify the pin configurations.

GREENTECH NOTE

The diodes covered in this chapter are based on the *pn* junction just like the solar cell, also known as the photovoltaic cell or PV cell, that was introduced in Chapter 1. A solar cell is basically a diode with a different geometric construction than rectifier and signal diodes. The *p* and *n* regions in the solar cell are much thinner to allow light energy to activate the photovoltaic effect, and a solar cell's exposed surface is transparent.



▲ **FIGURE 2–2**

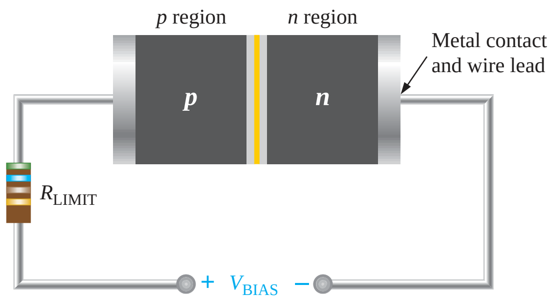
Typical diode packages with terminal identification. The letter K is used for cathode to avoid confusion with certain electrical quantities that are represented by *C*. Case type numbers are indicated for each diode.

Forward Bias

To **bias** a diode, you apply a dc voltage across it. **Forward bias** is the condition that allows current through the *pn* junction. Figure 2–3 shows a dc voltage source connected by conductive material (contacts and wire) across a diode in the direction to produce forward bias. This external bias voltage is designated as V_{BIAS}. The resistor limits the forward current to a value that will not damage the diode. Notice that the negative side of V_{BIAS} is connected to the *n* region of the diode and the positive side is connected to the *p* region. This is one requirement for forward bias. A second requirement is that the bias voltage, V_{BIAS}, must be greater than the **barrier potential**.

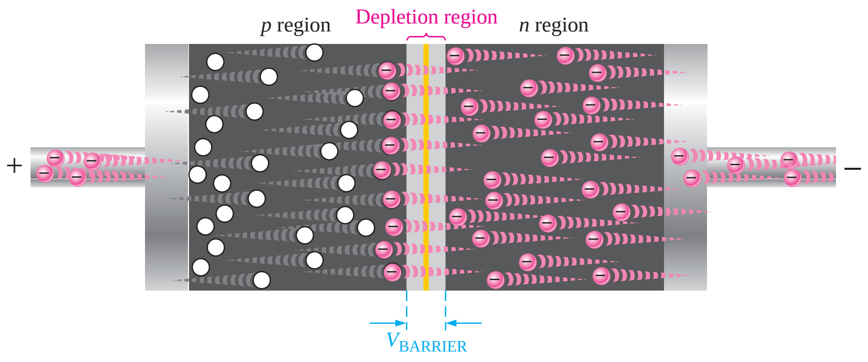
▶ **FIGURE 2–3**

A diode connected for forward bias.



A fundamental picture of what happens when a diode is forward-biased is shown in Figure 2–4. Because like charges repel, the negative side of the bias-voltage source "pushes" the free electrons, which are the majority carriers in the *n* region, toward the *pn* junction. This flow of free electrons is called *electron current.* The negative side of the source also provides a continuous flow of electrons through the external connection (conductor) and into the *n* region as shown.

The bias-voltage source imparts sufficient energy to the free electrons for them to overcome the barrier potential of the depletion region and move on through into the *p* region. Once in the *p* region, these conduction electrons have lost enough energy to immediately combine with holes in the valence band.



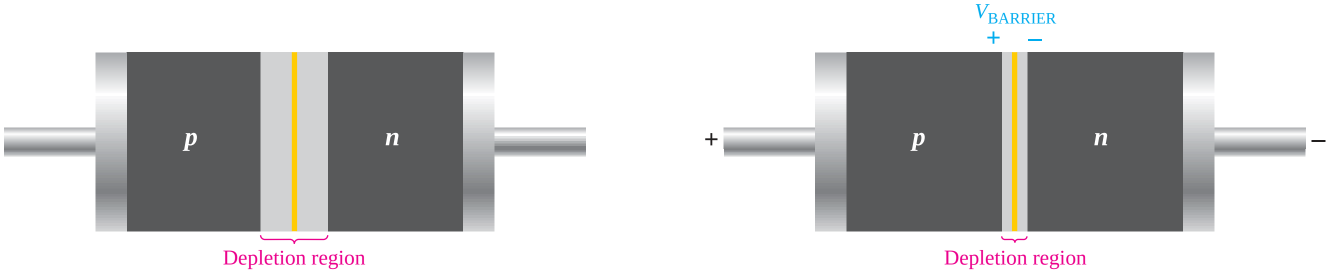
◀ FIGURE 2–4

A forward-biased diode showing the flow of majority carriers and the voltage due to the barrier potential across the depletion region.

Now, the electrons are in the valence band in the *p* region, simply because they have lost too much energy overcoming the barrier potential to remain in the conduction band. Since unlike charges attract, the positive side of the bias-voltage source attracts the valence electrons toward the left end of the *p* region. The holes in the *p* region provide the medium or "pathway" for these valence electrons to move through the *p* region. The valence electrons move from one hole to the next toward the left. The holes, which are the majority carriers in the *p* region, effectively (not actually) move to the right toward the junction, as you can see in Figure 2–4. This *effective* flow of holes is the hole current. You can also view the hole current as being created by the flow of valence electrons through the *p* region, with the holes providing the only means for these electrons to flow.

As the electrons flow out of the *p* region through the external connection (conductor) and to the positive side of the bias-voltage source, they leave holes behind in the *p* region; at the same time, these electrons become conduction electrons in the metal conductor. Recall that the conduction band in a conductor overlaps the valence band so that it takes much less energy for an electron to be a free electron in a conductor than in a semiconductor and that metallic conductors do not have holes in their structure. There is a continuous availability of holes effectively moving toward the *pn* junction to combine with the continuous stream of electrons as they come across the junction into the *p* region.

The Effect of Forward Bias on the Depletion Region As more electrons flow into the depletion region, the number of positive ions is reduced. As more holes effectively flow into the depletion region on the other side of the *pn* junction, the number of negative ions is reduced. This reduction in positive and negative ions during forward bias causes the depletion region to narrow, as indicated in Figure 2–5.



(a) At equilibrium (no bias)

(b) Forward bias narrows the depletion region and produces a voltage drop across the *pn* junction equal to the barrier potential.

▲ FIGURE 2–5

The depletion region narrows and a voltage drop is produced across the *pn* junction when the diode is forward-biased.

The Effect of the Barrier Potential During Forward Bias Recall that the electric field between the positive and negative ions in the depletion region on either side of the junction creates an "energy hill" that prevents free electrons from diffusing across the junction at equilibrium. This is known as the *barrier potential.*

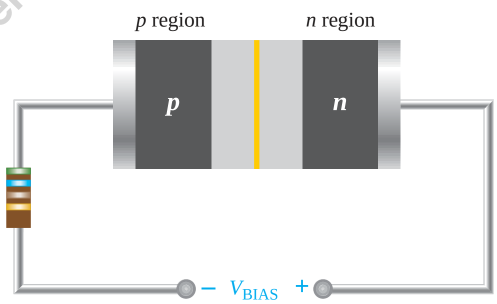
When forward bias is applied, the free electrons are provided with enough energy from the bias-voltage source to overcome the barrier potential and effectively "climb the energy hill" and cross the depletion region. The energy that the electrons require in order to pass through the depletion region is equal to the barrier potential. In other words, the electrons give up an amount of energy equivalent to the barrier potential when they cross the depletion region. This energy loss results in a voltage drop across the *pn* junction equal to the barrier potential (0.7 V), as indicated in Figure 2–5(b). An additional small voltage drop occurs across the *p* and *n* regions due to the internal resistance of the material. For doped semiconductive material, this resistance, called the **dynamic resistance,** is very small and can usually be neglected. This is discussed in more detail in Section 2–2.

Reverse Bias

Reverse bias is the condition that essentially prevents current through the diode. Figure 2–6 shows a dc voltage source connected across a diode in the direction to produce reverse bias. This external bias voltage is designated as V_{BIAS} just as it was for forward bias. Notice that the positive side of V_{BIAS} is connected to the *n* region of the diode and the negative side is connected to the *p* region. Also note that the depletion region is shown much wider than in forward bias or equilibrium.

▶ FIGURE 2–6

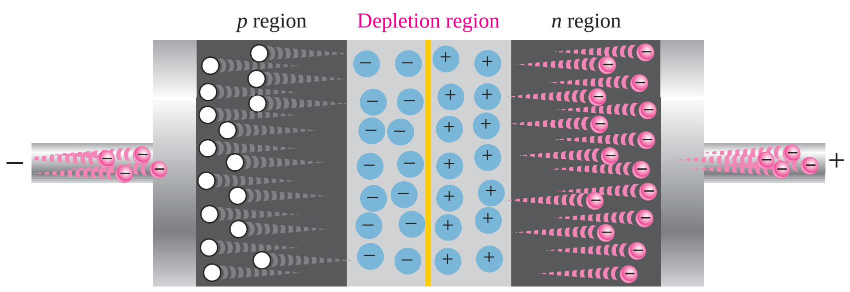
A diode connected for reverse bias. A limiting resistor is shown although it is not important in reverse bias because there is essentially no current.



An illustration of what happens when a diode is reverse-biased is shown in Figure 2–7. Because unlike charges attract, the positive side of the bias-voltage source "pulls" the free electrons, which are the majority carriers in the *n* region, away from the *pn* junction. As the electrons flow toward the positive side of the voltage source, additional positive ions are created. This results in a widening of the depletion region and a depletion of majority carriers.

▶ FIGURE 2–7

The diode during the short transition time immediately after reverse-bias voltage is applied.

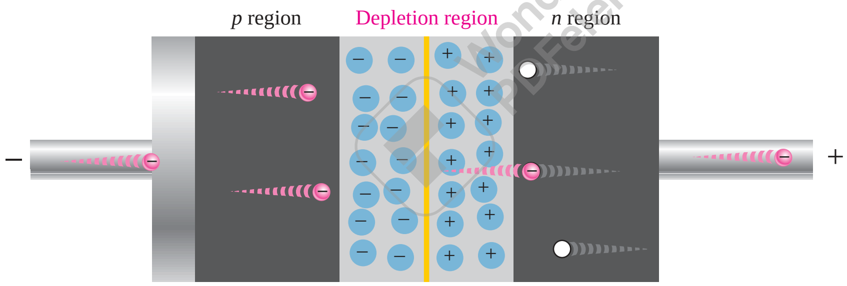


In the *p* region, electrons from the negative side of the voltage source enter as valence electrons and move from hole to hole toward the depletion region where they create additional negative ions. This results in a widening of the depletion region and a depletion of majority carriers. The flow of valence electrons can be viewed as holes being "pulled" toward the positive side.

The initial flow of charge carriers is transitional and lasts for only a very short time after the reverse-bias voltage is applied. As the depletion region widens, the availability of majority carriers decreases. As more of the *n* and *p* regions become depleted of majority carriers, the electric field between the positive and negative ions increases in strength until the potential across the depletion region equals the bias voltage, V_{BIAS}. At this point, the transition current essentially ceases except for a very small reverse current that can usually be neglected.

Reverse Current The extremely small current that exists in reverse bias after the transition current dies out is caused by the minority carriers in the *n* and *p* regions that are produced by thermally generated electron-hole pairs. The small number of free minority electrons in the *p* region are "pushed" toward the *pn* junction by the negative bias voltage. When these electrons reach the wide depletion region, they "fall down the energy hill" and combine with the minority holes in the *n* region as valence electrons and flow toward the positive bias voltage, creating a small hole current.

The conduction band in the *p* region is at a higher energy level than the conduction band in the *n* region. Therefore, the minority electrons easily pass through the depletion region because they require no additional energy. Reverse current is illustrated in Figure 2–8.



◀ FIGURE 2–8

The extremely small reverse current in a reverse-biased diode is due to the minority carriers from thermally generated electron-hole pairs.

Reverse Breakdown Normally, the reverse current is so small that it can be neglected. However, if the external reverse-bias voltage is increased to a value called the *breakdown voltage,* the reverse current will drastically increase.

This is what happens. The high reverse-bias voltage imparts energy to the free minority electrons so that as they speed through the *p* region, they collide with atoms with enough energy to knock valence electrons out of orbit and into the conduction band. The newly created conduction electrons are also high in energy and repeat the process. If one electron knocks only two others out of their valence orbit during its travel through the *p* region, the numbers quickly multiply. As these high-energy electrons go through the depletion region, they have enough energy to go through the *n* region as conduction electrons, rather than combining with holes.

The multiplication of conduction electrons just discussed is known as the **avalanche effect,** and reverse current can increase dramatically if steps are not taken to limit the current. When the reverse current is not limited, the resulting heating will permanently damage the diode. Most diodes are not operated in reverse breakdown, but if the current is limited (by adding a series-limiting resistor for example), there is no permanent damage to the diode.

SECTION 2–1 CHECKUP
Answers can be found at www.pearsonhighered.com/floyd.

1. Describe forward bias of a diode.
2. Explain how to forward-bias a diode.
3. Describe reverse bias of a diode.
4. Explain how to reverse-bias a diode.
5. Compare the depletion regions in forward bias and reverse bias.
6. Which bias condition produces majority carrier current?
7. How is reverse current in a diode produced?
8. When does reverse breakdown occur in a diode?
9. Define *avalanche effect* as applied to diodes.

2–2 VOLTAGE-CURRENT CHARACTERISTIC OF A DIODE

As you have learned, forward bias produces current through a diode and reverse bias essentially prevents current, except for a negligible reverse current. Reverse bias prevents current as long as the reverse-bias voltage does not equal or exceed the breakdown voltage of the junction. In this section, we will examine the relationship between the voltage and the current in a diode on a graphical basis.

After completing this section, you should be able to

- **Analyze the voltage-current (*V-I*) characteristic of a diode**
- Explain the *V-I* characteristic for forward bias
  - Graph the *V-I* curve for forward bias ◆ Describe how the barrier potential affects the *V-I* curve ◆ Define *dynamic resistance*
- Explain the *V-I* characteristic for reverse bias
  - Graph the *V-I* curve for reverse bias
- Discuss the complete *V-I* characteristic curve
  - Describe the effects of temperature on the diode characteristic

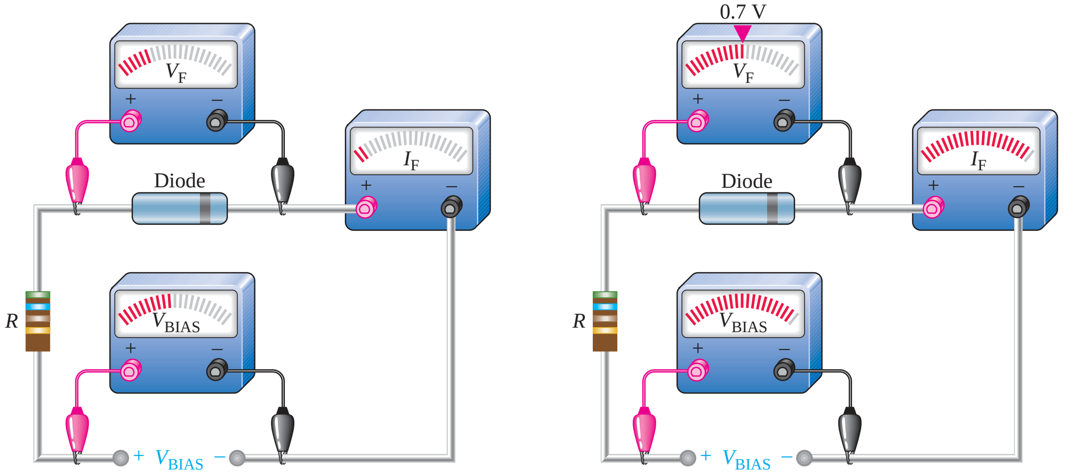
V-I Characteristic for Forward Bias

When a forward-bias voltage is applied across a diode, there is current. This current is called the *forward current* and is designated I_F. Figure 2–9 illustrates what happens as the forward-bias voltage is increased positively from 0 V. The resistor is used to limit the forward current to a value that will not overheat the diode and cause damage.

With 0 V across the diode, there is no forward current. As you gradually increase the forward-bias voltage, the forward current *and* the voltage across the diode gradually increase, as shown in Figure 2–9(a). A portion of the forward-bias voltage is dropped across the limiting resistor. When the forward-bias voltage is increased to a value where the voltage across the diode reaches approximately 0.7 V (barrier potential), the forward current begins to increase rapidly, as illustrated in Figure 2–9(b).

As you continue to increase the forward-bias voltage, the current continues to increase very rapidly, but the voltage across the diode increases only gradually above 0.7 V. This small increase in the diode voltage above the barrier potential is due to the voltage drop across the internal dynamic resistance of the semiconductive material.

Graphing the V-I Curve If you plot the results of the type of measurements shown in Figure 2–9 on a graph, you get the ***V-I* characteristic** curve for a forward-biased diode, as shown in Figure 2–10(a). The diode forward voltage (V_F) increases to the right along the horizontal axis, and the forward current (I_F) increases upward along the vertical axis.

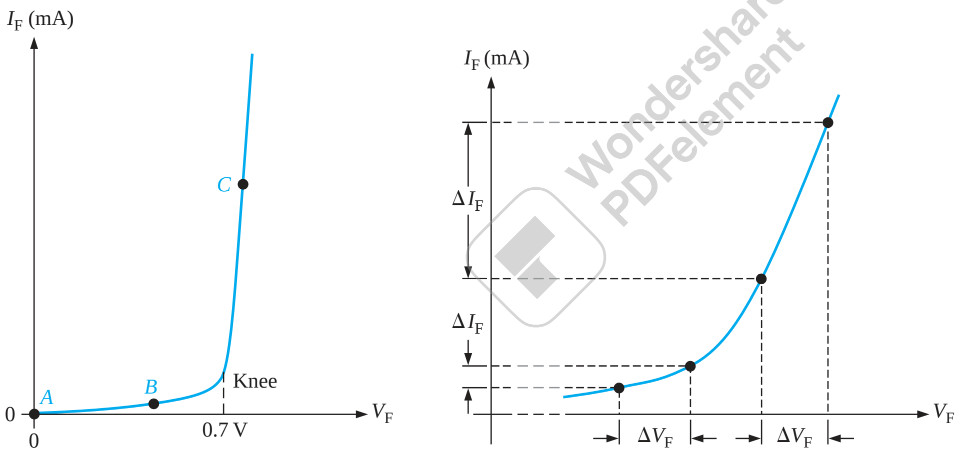


(a) Small forward-bias voltage ($V_F < 0.7$ V), very small forward current.

(b) Forward voltage reaches and remains nearly constant at approximately 0.7 V. Forward current continues to increase as the bias voltage is increased.

▲ **FIGURE 2–9**

Forward-bias measurements show general changes in V_F and I_F as V_{BIAS} is increased.



(a) *V-I* characteristic curve for forward bias.

(b) Expanded view of a portion of the curve in part (a). The dynamic resistance r'_d decreases as you move up the curve, as indicated by the decrease in the value of $\Delta V_F/\Delta I_F$.

◀ **FIGURE 2–10**

Relationship of voltage and current in a forward-biased diode.

As you can see in Figure 2–10(a), the forward current increases very little until the forward voltage across the *pn* junction reaches approximately 0.7 V at the knee of the curve. After this point, the forward voltage remains nearly constant at approximately 0.7 V, but I_F increases rapidly. As previously mentioned, there is a slight increase in V_F above 0.7 V as the current increases due mainly to the voltage drop across the dynamic resistance. The I_F scale is typically in mA, as indicated.

Three points *A*, *B*, and *C* are shown on the curve in Figure 2–10(a). Point *A* corresponds to a zero-bias condition. Point *B* corresponds to Figure 2–10(a) where the forward voltage is less than the barrier potential of 0.7 V. Point *C* corresponds to Figure 2–10(a) where the forward voltage *approximately* equals the barrier potential. As the external bias voltage and forward current continue to increase above the knee, the forward voltage will increase slightly above 0.7 V. In reality, the forward voltage can be as much as approximately 1 V, depending on the forward current.

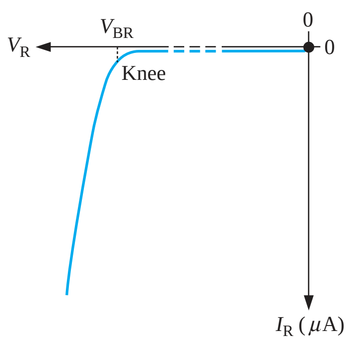
Dynamic Resistance Figure 2–10(b) is an expanded view of the *V-I* characteristic curve in part (a) and illustrates dynamic resistance. Unlike a linear resistance, the resistance of the forward-biased diode is not constant over the entire curve. Because the resistance changes as you move along the *V-I* curve, it is called *dynamic* or *ac resistance.* Internal resistances of electronic devices are usually designated by lowercase italic *r* with a prime, instead of the standard *R*. The dynamic resistance of a diode is designated r'_d.

Below the knee of the curve the resistance is greatest because the current increases very little for a given change in voltage ($r'_d = \Delta V_F/\Delta I_F$). The resistance begins to decrease in the region of the knee of the curve and becomes smallest above the knee where there is a large change in current for a given change in voltage.

V-I Characteristic for Reverse Bias

When a reverse-bias voltage is applied across a diode, there is only an extremely small reverse current (I_R) through the *pn* junction. With 0 V across the diode, there is no reverse current. As you gradually increase the reverse-bias voltage, there is a very small reverse current and the voltage across the diode increases. When the applied bias voltage is increased to a value where the reverse voltage across the diode (V_R) reaches the breakdown value (V_{BR}), the reverse current begins to increase rapidly.

As you continue to increase the bias voltage, the current continues to increase very rapidly, but the voltage across the diode increases very little above V_{BR}. Breakdown, with exceptions, is not a normal mode of operation for most *pn* junction devices.



▲ FIGURE 2–11

V-I characteristic curve for a reverse-biased diode.

Graphing the V-I Curve If you plot the results of reverse-bias measurements on a graph, you get the *V-I* characteristic curve for a reverse-biased diode. A typical curve is shown in Figure 2–11. The diode reverse voltage (V_R) increases to the left along the horizontal axis, and the reverse current (I_R) increases downward along the vertical axis.

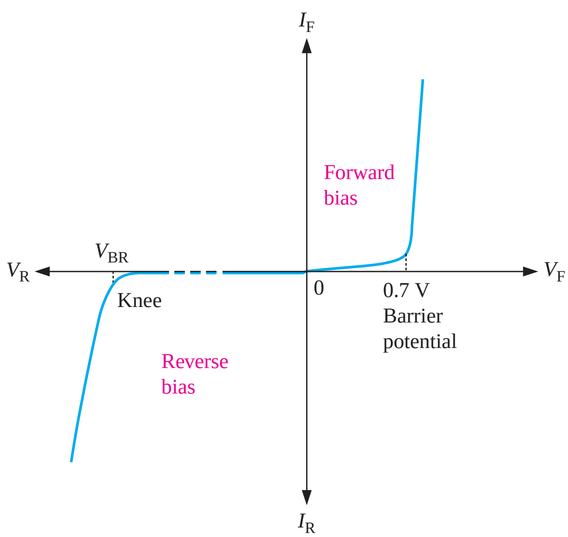
There is very little reverse current (usually μA or nA) until the reverse voltage across the diode reaches approximately the breakdown value (V_{BR}) at the knee of the curve. After this point, the reverse voltage remains at approximately V_{BR}, but I_R increases very rapidly, resulting in overheating and possible damage if current is not limited to a safe level. The breakdown voltage for a diode depends on the doping level, which the manufacturer sets, depending on the type of diode. A typical rectifier diode (the most widely used type) has a breakdown voltage of greater than 50 V. Some specialized diodes have a breakdown voltage that is only 5 V.

The Complete *V-I* Characteristic Curve

Combine the curves for both forward bias and reverse bias, and you have the complete *V-I* characteristic curve for a diode, as shown in Figure 2–12.

► FIGURE 2–12

The complete *V-I* characteristic curve for a diode.



Temperature Effects For a forward-biased diode, as temperature is increased, the forward current increases for a given value of forward voltage. Also, for a given value of forward current, the forward voltage decreases. This is shown with the *V-I* characteristic curves in Figure 2–13. The blue curve is at room temperature (25°C) and the red curve is at an elevated temperature (25°C + ΔT). The barrier potential decreases by 2 mV for each degree increase in temperature.

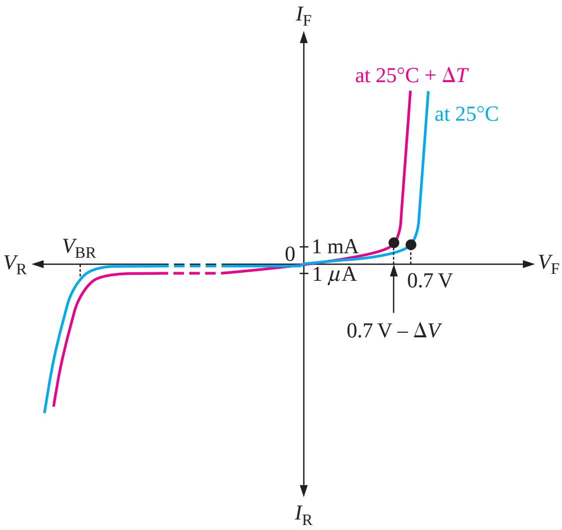


FIGURE 2–13

Temperature effect on the diode *V-I* characteristic. The 1 mA and 1 μA marks on the vertical axis are given as a basis for a relative comparison of the current scales.

For a reverse-biased diode, as temperature is increased, the reverse current increases. The difference in the two curves is exaggerated on the graph in Figure 2–13 for illustration. Keep in mind that the reverse current below breakdown remains extremely small and can usually be neglected.

SECTION 2–2 CHECKUP

1. Discuss the significance of the knee of the characteristic curve in forward bias.
2. On what part of the curve is a forward-biased diode normally operated?
3. Which is greater, the breakdown voltage or the barrier potential?
4. On what part of the curve is a reverse-biased diode normally operated?
5. What happens to the barrier potential when the temperature increases?

2–3 Diode Models

You have learned that a diode is a *pn* junction device. In this section, you will learn the electrical symbol for a diode and how a diode can be modeled for circuit analysis using any one of three levels of complexity. Also, diode packaging and terminal identification are introduced.

After completing this section, you should be able to

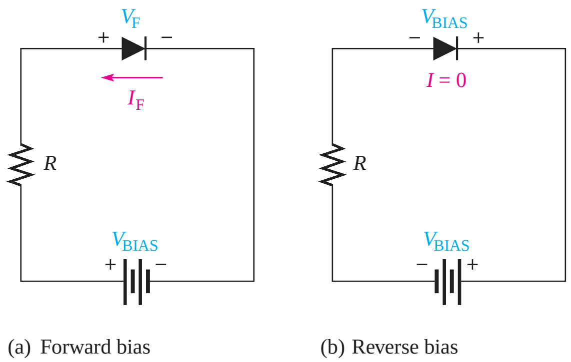
- **Explain how the three diode models differ**
- Discuss bias connections
- Describe the diode approximations
  - Describe the ideal diode model
  - Describe the practical diode model
  - Describe the complete diode model

Bias Connections

Forward-Bias Recall that a diode is forward-biased when a voltage source is connected as shown in Figure 2–14(a). The positive terminal of the source is connected to the anode through a current-limiting resistor. The negative terminal of the source is connected to the cathode. The forward current (I_F) is from cathode to anode as indicated. The forward voltage drop (V_F) due to the barrier potential is from positive at the anode to negative at the cathode.

▶ FIGURE 2–14

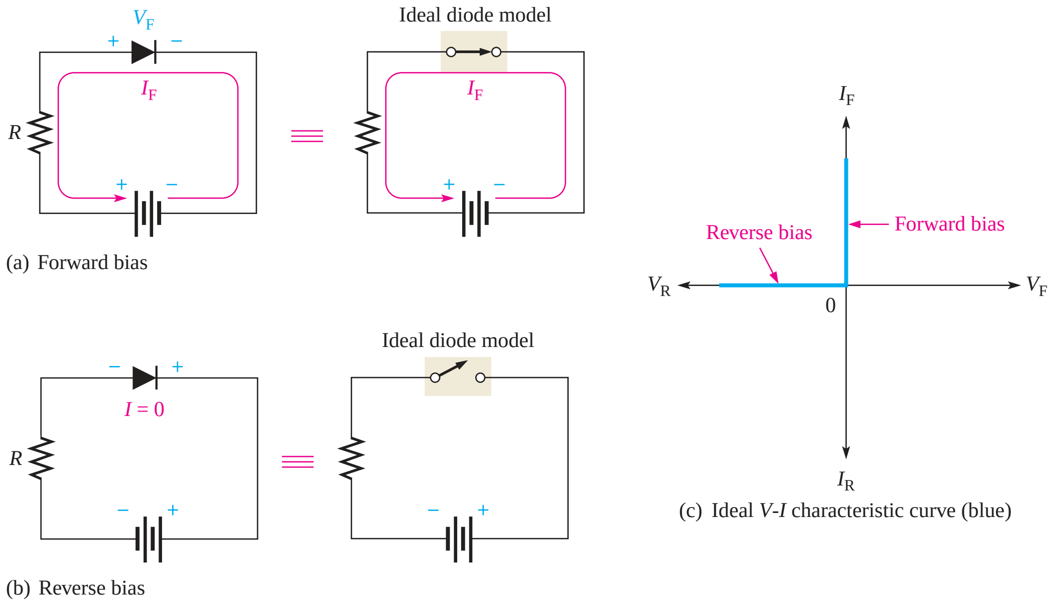
Forward-bias and reverse-bias connections showing the diode symbol.



Reverse-Bias Connection A diode is reverse-biased when a voltage source is connected as shown in Figure 2–14(b). The negative terminal of the source is connected to the anode side of the circuit, and the positive terminal is connected to the cathode side. A resistor is not necessary in reverse bias but it is shown for circuit consistency. The reverse current is extremely small and can be considered to be zero. Notice that the entire bias voltage (V_{BIAS}) appears across the diode.

Diode Approximations

The Ideal Diode Model The ideal model of a diode is the least accurate approximation and can be represented by a simple switch. When the diode is forward-biased, it ideally acts like a closed (on) switch, as shown in Figure 2–15(a). When the diode is reverse-biased, it



▲ FIGURE 2–15

The ideal model of a diode.

ideally acts like an open (off) switch, as shown in part (b). Although the barrier potential, the forward dynamic resistance, and the reverse current are all neglected, this model is adequate for most troubleshooting when you are trying to determine if the diode is working properly.

In Figure 2–15(c), the ideal *V-I* characteristic curve graphically depicts the ideal diode operation. Since the barrier potential and the forward dynamic resistance are neglected, the diode is assumed to have a zero voltage across it when forward-biased, as indicated by the portion of the curve on the positive vertical axis.

$$V_F = 0\ \text{V}$$

The forward current is determined by the bias voltage and the limiting resistor using Ohm's law.

$$I_F = \frac{V_{BIAS}}{R_{LIMIT}}$$

Equation 2–1

Since the reverse current is neglected, its value is assumed to be zero, as indicated in Figure 2–15(c) by the portion of the curve on the negative horizontal axis.

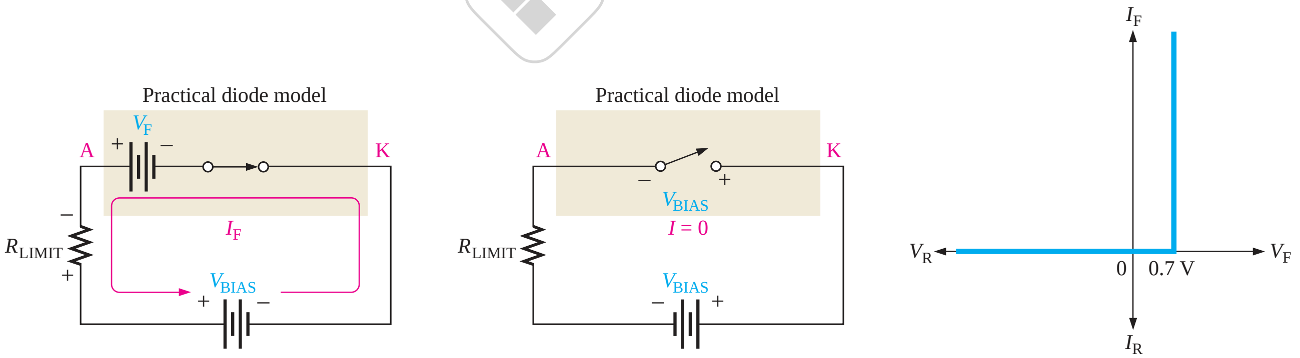
$$I_R = 0\ \text{A}$$

The reverse voltage equals the bias voltage.

$$V_R = V_{BIAS}$$

You may want to use the ideal model when you are troubleshooting or trying to figure out the operation of a circuit and are not concerned with more exact values of voltage or current.

The Practical Diode Model The practical model includes the barrier potential. When the diode is forward-biased, it is equivalent to a closed switch in series with a small equivalent voltage source (V_F) equal to the barrier potential (0.7 V) with the positive side toward the anode, as indicated in Figure 2–16(a). This equivalent voltage source represents the barrier potential that must be exceeded by the bias voltage before the diode will conduct and is not an active source of voltage. When conducting, a voltage drop of 0.7 V appears across the diode.



(a) Forward bias (b) Reverse bias (c) Characteristic curve (silicon)

▲ **FIGURE 2–16**

The practical model of a diode.

When the diode is reverse-biased, it is equivalent to an open switch just as in the ideal model, as shown in Figure 2–16(b). The barrier potential does not affect reverse bias, so it is not a factor.

The characteristic curve for the practical diode model is shown in Figure 2–16(c). Since the barrier potential is included and the dynamic resistance is neglected, the diode is assumed to have a voltage across it when forward-biased, as indicated by the portion of the curve to the right of the origin.

$$V_F = 0.7\ \text{V}$$

The forward current is determined as follows by first applying Kirchhoff's voltage law to Figure 2–16(a):

$$V_{\text{BIAS}} - V_{\text{F}} - V_{R_{\text{LIMIT}}} = 0$$
$$V_{R_{\text{LIMIT}}} = I_{\text{F}}R_{\text{LIMIT}}$$

Substituting and solving for I_{F},

Equation 2–2

$$\boldsymbol{I_{\text{F}} = \frac{V_{\text{BIAS}} - V_{\text{F}}}{R_{\text{LIMIT}}}}$$

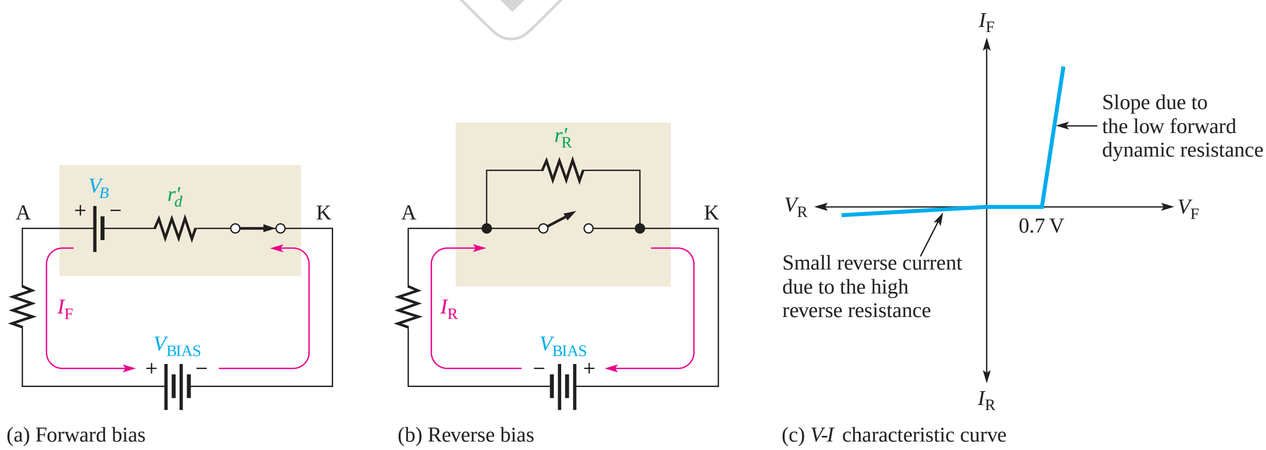
The diode is assumed to have zero reverse current, as indicated by the portion of the curve on the negative horizontal axis.

$$I_{\text{R}} = 0\text{ A}$$
$$V_{\text{R}} = V_{\text{BIAS}}$$

The practical model is useful when you are troubleshooting in lower-voltage circuits. In these cases, the 0.7 V drop across the diode may be significant and should be taken into account. The practical model is also useful when you are designing basic diode circuits.

The Complete Diode Model The complete model of a diode is the most accurate approximation and includes the barrier potential, the small forward dynamic resistance (r'_d), and the large internal reverse resistance (r'_{R}). The reverse resistance is taken into account because it provides a path for the reverse current, which is included in this diode model.

When the diode is forward-biased, it acts as a closed switch in series with the equivalent barrier potential voltage (V_B) and the small forward dynamic resistance (r'_d), as indicated in Figure 2–17(a). When the diode is reverse-biased, it acts as an open switch in parallel with the large internal reverse resistance (r'_{R}), as shown in Figure 2–17(b). The barrier potential does not affect reverse bias, so it is not a factor.



▲ FIGURE 2–17

The complete model of a diode.

The characteristic curve for the complete diode model is shown in Figure 2–17(c). Since the barrier potential and the forward dynamic resistance are included, the diode is assumed to have a voltage across it when forward-biased. This voltage (V_{F}) consists of the barrier potential voltage plus the small voltage drop across the dynamic resistance, as indicated by the portion of the curve to the right of the origin. The curve slopes because the voltage drop due to dynamic resistance increases as the current increases. For the complete model of a silicon diode, the following formulas apply:

$$V_F = 0.7\text{ V} + I_F r'_d$$

$$I_F = \frac{V_{BIAS} - 0.7\text{ V}}{R_{LIMIT} + r'_d}$$

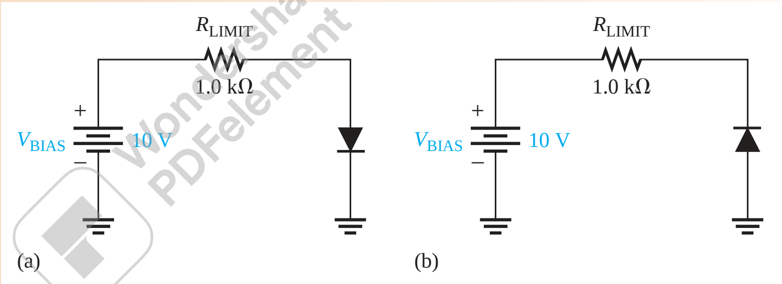
The reverse current is taken into account with the parallel resistance and is indicated by the portion of the curve to the left of the origin. The breakdown portion of the curve is not shown because breakdown is not a normal mode of operation for most diodes.

For troubleshooting work, it is unnecessary to use the complete model, as it involves complicated calculations. This model is generally suited to design problems using a computer for simulation. The ideal and practical models are used for circuits in this text, except in the following example, which illustrates the differences in the three models.

EXAMPLE 2–1

(a) Determine the forward voltage and forward current for the diode in Figure 2–18(a) for each of the diode models. Also find the voltage across the limiting resistor in each case. Assume $r'_d = 10\ \Omega$ at the determined value of forward current.

(b) Determine the reverse voltage and reverse current for the diode in Figure 2–18(b) for each of the diode models. Also find the voltage across the limiting resistor in each case. Assume $I_R = 1\ \mu\text{A}$.



▲ FIGURE 2–18

Solution **(a)** Ideal model:

$$V_F = \mathbf{0\ V}$$

$$I_F = \frac{V_{BIAS}}{R_{LIMIT}} = \frac{10\text{ V}}{1.0\text{ k}\Omega} = \mathbf{10\ mA}$$

$$V_{R_{LIMIT}} = I_F R_{LIMIT} = (10\text{ mA})(1.0\text{ k}\Omega) = \mathbf{10\ V}$$

Practical model:

$$V_F = \mathbf{0.7\ V}$$

$$I_F = \frac{V_{BIAS} - V_F}{R_{LIMIT}} = \frac{10\text{ V} - 0.7\text{ V}}{1.0\text{ k}\Omega} = \frac{9.3\text{ V}}{1.0\text{ k}\Omega} = \mathbf{9.3\ mA}$$

$$V_{R_{LIMIT}} = I_F R_{LIMIT} = (9.3\text{ mA})(1.0\text{ k}\Omega) = \mathbf{9.3\ V}$$

Complete model:

$$I_F = \frac{V_{BIAS} - 0.7\text{ V}}{R_{LIMIT} + r'_d} = \frac{10\text{ V} - 0.7\text{ V}}{1.0\text{ k}\Omega + 10\ \Omega} = \frac{9.3\text{ V}}{1010\ \Omega} = \mathbf{9.21\ mA}$$

$$V_F = 0.7\ V + I_F r'_d = 0.7\text{ V} + (9.21\text{ mA})(10\ \Omega) = \mathbf{792\ mV}$$

$$V_{R_{LIMIT}} = I_F R_{LIMIT} = (9.21\text{ mA})(1.0\text{ k}\Omega) = \mathbf{9.21\ V}$$

(b) Ideal model:

$$I_R = \mathbf{0\ A}$$
$$V_R = V_{BIAS} = \mathbf{10\ V}$$
$$V_{R_{LIMIT}} = \mathbf{0\ V}$$

Practical model:

$$I_R = \mathbf{0\ A}$$
$$V_R = V_{BIAS} = \mathbf{10\ V}$$
$$V_{R_{LIMIT}} = \mathbf{0\ V}$$

Complete model:

$$I_R = \mathbf{1\ \mu A}$$
$$V_{R_{LIMIT}} = I_R R_{LIMIT} = (1\ \mu A)(1.0\ k\Omega) = \mathbf{1\ mV}$$
$$V_R = V_{BIAS} - V_{R_{LIMIT}} = 10\ V - 1\ mV = \mathbf{9.999\ V}$$

Related Problem[*] Assume that the diode in Figure 2–18(a) fails open. What is the voltage across the diode and the voltage across the limiting resistor?

---

[*]**Answers can be found at www.pearsonhighered.com/floyd.**

Open the Multisim file E02-01 in the Examples folder on the companion website. Measure the voltages across the diode and the resistor in both circuits and compare with the calculated results in this example.

SECTION 2–3 CHECKUP

1. What are the two conditions under which a diode is operated?
2. Under what condition is a diode never intentionally operated?
3. What is the simplest way to visualize a diode?
4. To more accurately represent a diode, what factors must be included?
5. Which diode model represents the most accurate approximation?

2–4 HALF-WAVE RECTIFIERS

Because of their ability to conduct current in one direction and block current in the other direction, diodes are used in circuits called rectifiers that convert ac voltage into dc voltage. Rectifiers are found in all dc power supplies that operate from an ac voltage source. A power supply is an essential part of each electronic system from the simplest to the most complex.

After completing this section, you should be able to

- **Explain and analyze the operation of half-wave rectifiers**
- Describe a basic dc power supply
- Discuss half-wave rectification
  - Determine the average value of a half-wave voltage
- Explain how the barrier potential affects a half-wave rectifier output
  - Calculate the output voltage
- Define *peak inverse voltage*
- Explain the operation of a transformer-coupled rectifier

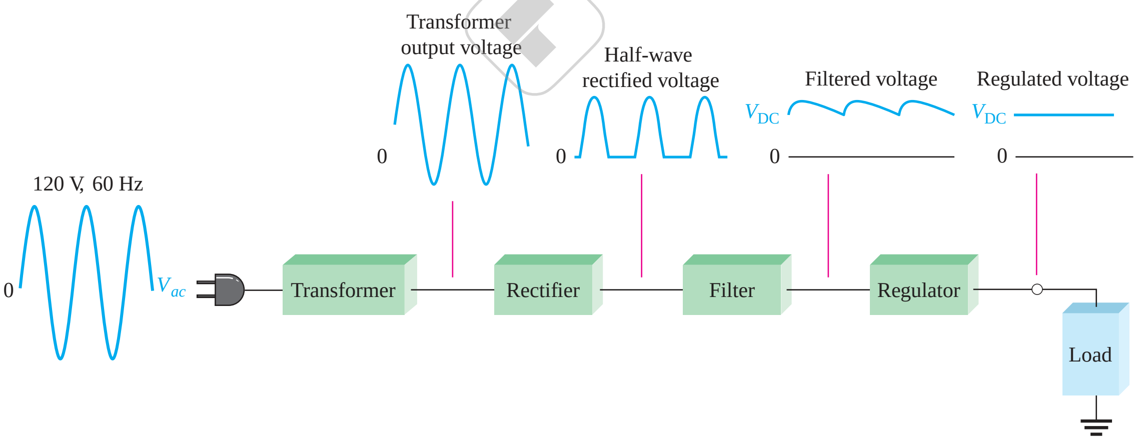
The Basic DC Power Supply

All active electronic devices require a source of constant dc that can be supplied by a battery or a dc power supply. The **dc power supply** converts the standard 120 V, 60 Hz ac voltage available at wall outlets into a constant dc voltage. The dc power supply is one of the most common circuits you will find, so it is important to understand how it works. The voltage produced is used to power all types of electronic circuits including consumer electronics (televisions, DVDs, etc.), computers, industrial controllers, and most laboratory instrumentation systems and equipment. The dc voltage level required depends on the application, but most applications require relatively low voltages.

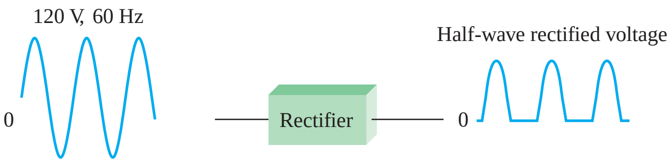
A basic block diagram of the complete power supply is shown in Figure 2–19(a). Generally the ac input line voltage is stepped down to a lower ac voltage with a transformer (although it may be stepped up when higher voltages are needed or there may be no transformer at all in rare instances). As you learned in your dc/ac course, a **transformer** changes ac voltages based on the turns ratio between the primary and secondary. If the secondary has more turns than the primary, the output voltage across the secondary will be higher and the current will be smaller. If the secondary has fewer turns than the primary, the output voltage across the secondary will be lower and the current will be higher. The rectifier can be either a half-wave rectifier or a full-wave rectifier (covered in Section 2–5). The **rectifier** converts the ac input voltage to a pulsating dc voltage, called a half-wave rectified voltage, as shown in Figure 2–19(b). The **filter** eliminates the fluctuations in the rectified voltage and produces a relatively smooth dc voltage. The power supply filter is covered in Section 2–6. The **regulator** is a circuit that maintains a constant dc voltage for variations in the input line voltage or in the load. Regulators vary from a single semiconductor device to more complex integrated circuits. The load is a circuit or device connected to the output of the power supply and operates from the power supply voltage and current.

FYI

The standard line voltage in North America is 120 V/240 V at 60 Hz. Most small appliances operate on 120 V and larger appliances such as dryers, ranges, and heaters operate on 240 V. Occasionally, you will see references to 110 V or 115 V, but the standard is 120 V. Some foreign countries do use 110 V or 115 V at either 60 Hz or 50 Hz.



(a) Complete power supply with transformer, rectifier, filter, and regulator



(b) Half-wave rectifier

▲ **FIGURE 2–19**

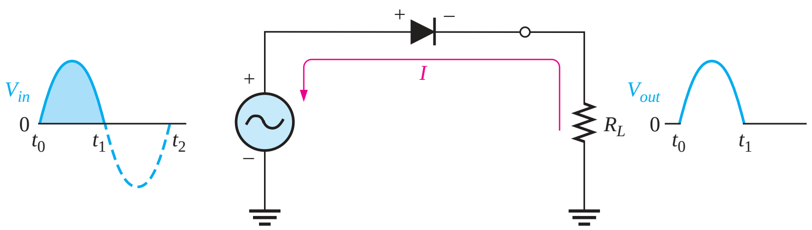
Block diagram of a dc power supply with a load and a rectifier.

GREENTECH NOTE

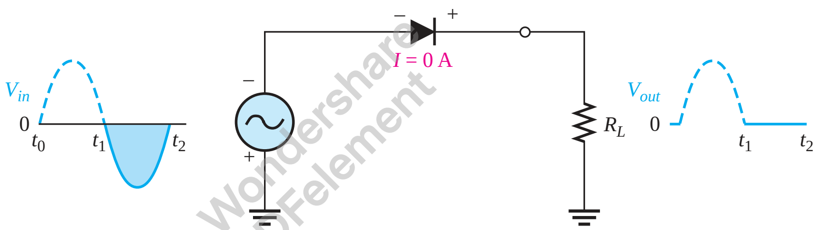
The *Energy Star* program was originally established by the EPA as a voluntary labeling program designed to indicate energy-efficient products. In order for power supplies to comply with the Energy Star requirements, they must have a minimum 80% efficiency rating for all rated power output. Try to choose a power supply that carries as 80 PLUS logo on it. This means that the power supply efficiency has been tested and approved to meet the Energy Star guidelines. Not all power supplies that claim to be high efficiency meet the Energy Star requirements.

Half-Wave Rectifier Operation

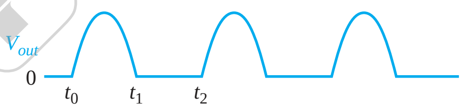
Figure 2–20 illustrates the process called *half-wave rectification*. A diode is connected to an ac source and to a load resistor, R_L, forming a **half-wave rectifier**. Keep in mind that all ground symbols represent the same point electrically. Let's examine what happens during one cycle of the input voltage using the ideal model for the diode. When the sinusoidal input voltage (V_{in}) goes positive, the diode is forward-biased and conducts current through the load resistor, as shown in part (a). The current produces an output voltage across the load R_L, which has the same shape as the positive half-cycle of the input voltage.



(a) During the positive alternation of the 60 Hz input voltage, the output voltage looks like the positive half of the input voltage. The current path is through ground back to the source.



(b) During the negative alternation of the input voltage, the current is 0, so the output voltage is also 0.



(c) 60 Hz half-wave output voltage for three input cycles

▲ **FIGURE 2–20**

Half-wave rectifier operation. The diode is considered to be ideal.

When the input voltage goes negative during the second half of its cycle, the diode is reverse-biased. There is no current, so the voltage across the load resistor is 0 V, as shown in Figure 2–20(b). The net result is that only the positive half-cycles of the ac input voltage appear across the load. Since the output does not change polarity, it is a pulsating dc voltage with a frequency of 60 Hz, as shown in part (c).

Average Value of the Half-Wave Output Voltage The average value of the half-wave rectified output voltage is the value you would measure on a dc voltmeter. Mathematically, it is determined by finding the area under the curve over a full cycle, as illustrated in Figure 2–21, and then dividing by 2π, the number of radians in a full cycle. The result of this is expressed in Equation 2–3, where V_p is the peak value of the voltage. This equation shows that V_{AVG} is approximately 31.8% of V_p for a half-wave rectified voltage. The derivation for this equation can be found in "Derivations of Selected Equations" at www.pearsonhighered.com/floyd.

Equation 2–3

$$V_{AVG} = \frac{V_p}{\pi}$$

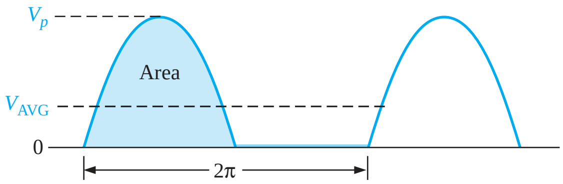


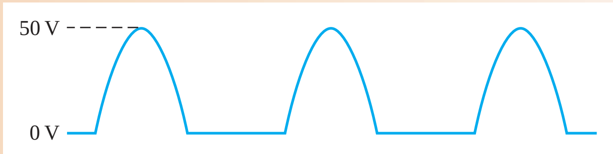
FIGURE 2–21

Average value of the half-wave rectified signal.

EXAMPLE 2–2

What is the average value of the half-wave rectified voltage in Figure 2–22?

FIGURE 2–22



Solution

$$V_{AVG} = \frac{V_p}{\pi} = \frac{50\text{ V}}{\pi} = \mathbf{15.9\text{ V}}$$

Notice that V_{AVG} is 31.8% of V_p.

Related Problem Determine the average value of the half-wave voltage if its peak amplitude is 12 V.

Effect of the Barrier Potential on the Half-Wave Rectifier Output

In the previous discussion, the diode was considered ideal. When the practical diode model is used with the barrier potential of 0.7 V taken into account, this is what happens. During the positive half-cycle, the input voltage must overcome the barrier potential before the diode becomes forward-biased. This results in a half-wave output with a peak value that is 0.7 V less than the peak value of the input, as shown in Figure 2–23. The expression for the peak output voltage is

$$V_{p(out)} = V_{p(in)} - 0.7\text{ V} \qquad \text{Equation 2–4}$$

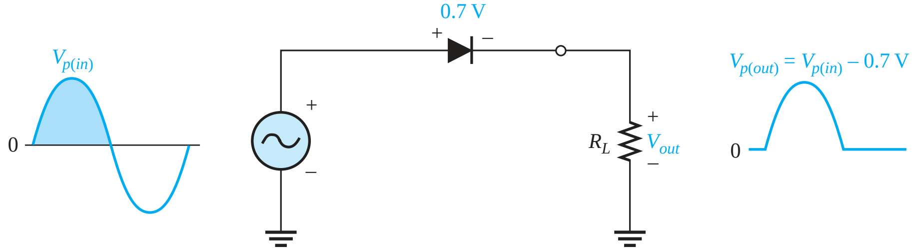
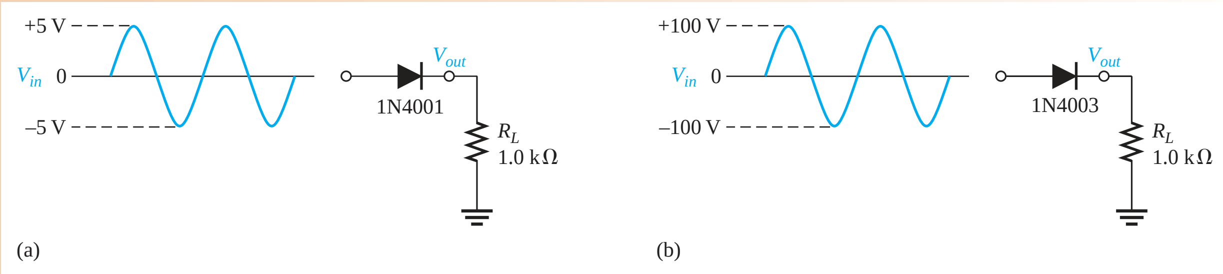


FIGURE 2–23

The effect of the barrier potential on the half-wave rectified output voltage is to reduce the peak value of the input by about 0.7 V.

It is usually acceptable to use the ideal diode model, which neglects the effect of the barrier potential, when the peak value of the applied voltage is much greater than the barrier potential (at least 10 V, as a rule of thumb). However, we will use the practical model of a diode, taking the 0.7 V barrier potential into account unless stated otherwise.

EXAMPLE 2–3 Draw the output voltages of each rectifier for the indicated input voltages, as shown in Figure 2–24. The 1N4001 and 1N4003 are specific rectifier diodes.



▲ **FIGURE 2–24**

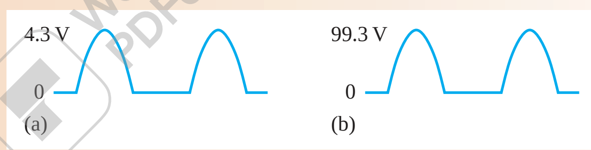
Solution The peak output voltage for circuit (a) is

$$V_{p(out)} = V_{p(in)} - 0.7\text{ V} = 5\text{ V} - 0.7\text{ V} = \mathbf{4.30\text{ V}}$$

The peak output voltage for circuit (b) is

$$V_{p(out)} = V_{p(in)} - 0.7\text{ V} = 100\text{ V} - 0.7\text{ V} = \mathbf{99.3\text{ V}}$$

The output voltage waveforms are shown in Figure 2–25. Note that the barrier potential could have been neglected in circuit (b) with very little error (0.7 percent); but, if it is neglected in circuit (a), a significant error results (14 percent).



▲ **FIGURE 2–25**

Output voltages for the circuits in Figure 2–24. They are not shown on the same scale.

Related Problem Determine the peak output voltages for the rectifiers in Figure 2–24 if the peak input in part (a) is 3 V and the peak input in part (b) is 50 V.

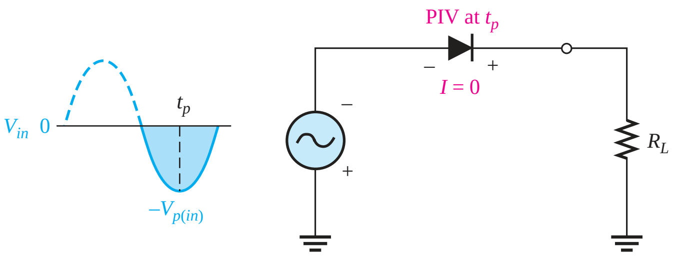
Open the Multisim file E02-03 in the Examples folder on the companion website. For the inputs specified in the example, measure the resulting output voltage waveforms. Compare your measured results with those shown in the example.

Peak Inverse Voltage (PIV)

The **peak inverse voltage (PIV)** equals the peak value of the input voltage, and the diode must be capable of withstanding this amount of repetitive reverse voltage. For the diode in Figure 2–26, the maximum value of reverse voltage, designated as PIV, occurs at the peak of each negative alternation of the input voltage when the diode is reverse-biased. A diode should be rated at least 20% higher than the PIV.

Equation 2–5

$$\mathbf{PIV} = V_{p(in)}$$

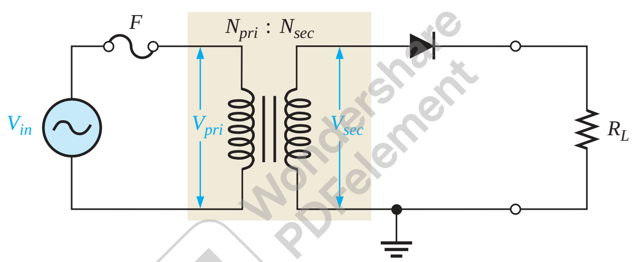


▲ FIGURE 2–26

The PIV occurs at the peak of each half-cycle of the input voltage when the diode is reverse-biased. In this circuit, the PIV occurs at the peak of each negative half-cycle.

Transformer Coupling

As you have seen, a transformer is often used to couple the ac input voltage from the source to the rectifier, as shown in Figure 2–27. Transformer coupling provides two advantages. First, it allows the source voltage to be stepped down as needed. Second, the ac source is electrically isolated from the rectifier, thus preventing a shock hazard in the secondary circuit.



◄ FIGURE 2–27

Half-wave rectifier with transformer-coupled input voltage.

The amount that the voltage is stepped down is determined by the **turns ratio** of the transformer. Unfortunately, the definition of turns ratio for transformers is not consistent between various sources and disciplines. In this text, we use the definition given by the IEEE for electronic power transformers, which is "the number of turns in the secondary (N_{sec}) divided by the number of turns in the primary (N_{pri})." Thus, a transformer with a turns ratio less than 1 is a step-down type and one with a turns ratio greater than 1 is a step-up type. To show the turns ratio on a schematic, it is common practice to show the numerical ratio directly above the windings.

The secondary voltage of a transformer equals the turns ratio, n, times the primary voltage.

$$V_{sec} = nV_{pri}$$

If $n > 1$, the secondary voltage is greater than the primary voltage. If $n < 1$, the secondary voltage is less than the primary voltage. If $n = 1$, then $V_{sec} = V_{pri}$.

The peak secondary voltage, $V_{p(sec)}$, in a transformer-coupled half-wave rectifier is the same as $V_{p(in)}$ in Equation 2–4. Therefore, Equation 2–4 written in terms of $V_{p(sec)}$ is

$$V_{p(out)} = V_{p(sec)} - 0.7\text{ V}$$

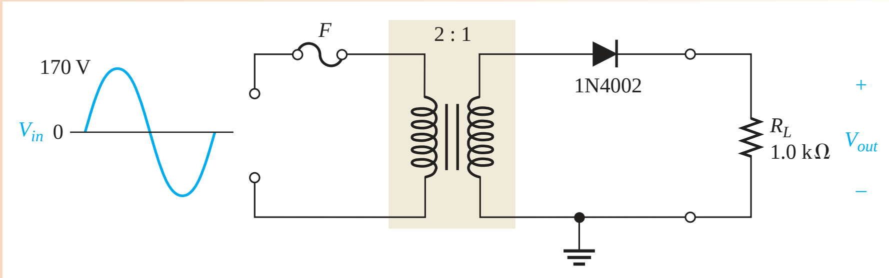
and Equation 2–5 in terms of $V_{p(sec)}$ is

$$\text{PIV} = V_{p(sec)}$$

Turns ratio is useful for understanding the voltage transfer from primary to secondary. However, transformer datasheets rarely show the turns ratio. A transformer is generally specified based on the secondary voltage rather than the turns ratio.

EXAMPLE 2–4 Determine the peak value of the output voltage for Figure 2–28 if the turns ratio is 0.5.

▶ FIGURE 2–28



Solution

$$V_{p(pri)} = V_{p(in)} = 170 \text{ V}$$

The peak secondary voltage is

$$V_{p(sec)} = nV_{p(pri)} = 0.5(170 \text{ V}) = 85 \text{ V}$$

The rectified peak output voltage is

$$V_{p(out)} = V_{p(sec)} - 0.7 \text{ V} = 85 \text{ V} - 0.7 \text{ V} = \mathbf{84.3 \text{ V}}$$

where $V_{p(sec)}$ is the input to the rectifier.

Related Problem

(a) Determine the peak value of the output voltage for Figure 2–28 if $n = 2$ and $V_{p(in)} = 312$ V.
(b) What is the PIV across the diode?
(c) Describe the output voltage if the diode is turned around.

Open the Multisim file E02-04 in the Examples folder on the companion website. For the specified input, measure the peak output voltage. Compare your measured result with the calculated value.

SECTION 2–4 CHECKUP

1. At what point on the input cycle does the PIV occur?
2. For a half-wave rectifier, there is current through the load for approximately what percentage of the input cycle?
3. What is the average of a half-wave rectified voltage with a peak value of 10 V?
4. What is the peak value of the output voltage of a half-wave rectifier with a peak sine wave input of 25 V?
5. What PIV rating must a diode have to be used in a rectifier with a peak output voltage of 50 V?

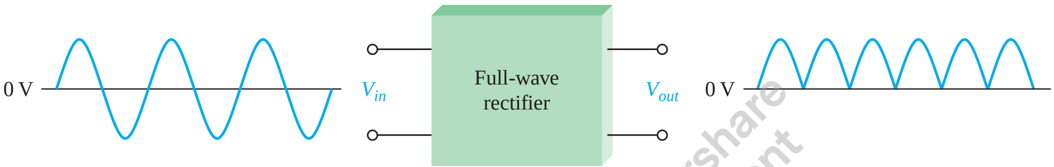
2–5 FULL-WAVE RECTIFIERS

Although half-wave rectifiers have some applications, the full-wave rectifier is the most commonly used type in dc power supplies. In this section, you will use what you learned about half-wave rectification and expand it to full-wave rectifiers. You will learn about two types of full-wave rectifiers: center-tapped and bridge.

After completing this section, you should be able to

- **Explain and analyze the operation of full-wave rectifiers**
- Describe how a center-tapped full-wave rectifier works
  - ◆ Discuss the effect of the turns ratio on the rectifier output ◆ Calculate the peak inverse voltage
- Describe how a bridge full-wave rectifier works
  - ◆ Determine the bridge output voltage ◆ Calculate the peak inverse voltage

A **full-wave rectifier** allows unidirectional (one-way) current through the load during the entire 360° of the input cycle, whereas a half-wave rectifier allows current through the load only during one-half of the cycle. The result of full-wave rectification is an output voltage with a frequency twice the input frequency and that pulsates every half-cycle of the input, as shown in Figure 2–29.



▲ FIGURE 2–29

Full-wave rectification.

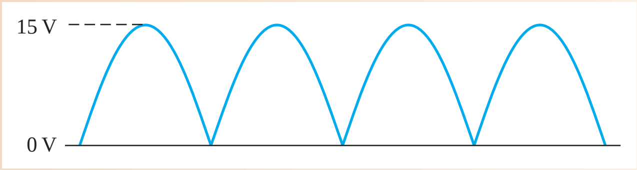
The number of positive alternations that make up the full-wave rectified voltage is twice that of the half-wave voltage for the same time interval. The average value, which is the value measured on a dc voltmeter, for a full-wave rectified sinusoidal voltage is twice that of the half-wave, as shown in the following formula:

$$\mathbf{V_{AVG} = \frac{2V_p}{\pi}}$$ **Equation 2–6**

V_{AVG} is approximately 63.7% of V_p for a full-wave rectified voltage.

EXAMPLE 2–5 Find the average value of the full-wave rectified voltage in Figure 2–30.

► FIGURE 2–30



Solution

$$V_{AVG} = \frac{2V_p}{\pi} = \frac{2(15\text{ V})}{\pi} = \mathbf{9.55\ V}$$

V_{AVG} is 63.7% of V_p.

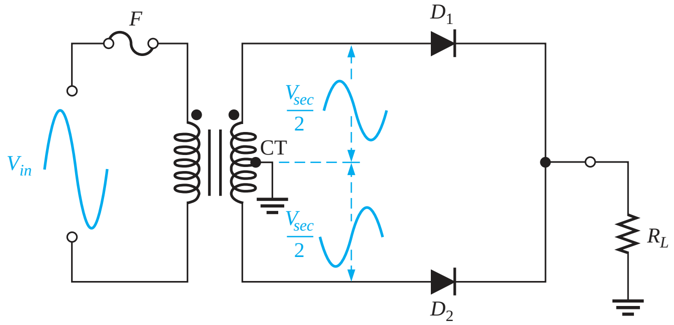
Related Problem Find the average value of the full-wave rectified voltage if its peak is 155 V.

Center-Tapped Full-Wave Rectifier Operation

A **center-tapped rectifier** is a type of full-wave rectifier that uses two diodes connected to the secondary of a center-tapped transformer, as shown in Figure 2–31. The input voltage is coupled through the transformer to the center-tapped secondary. Half of the total secondary voltage appears between the center tap and each end of the secondary winding as shown.

▶ FIGURE 2–31

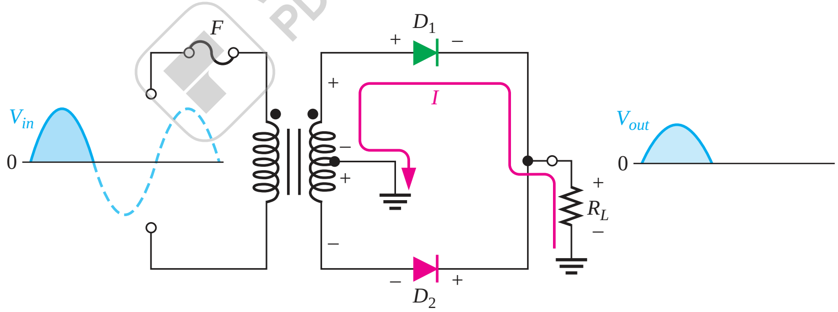
A center-tapped full-wave rectifier.



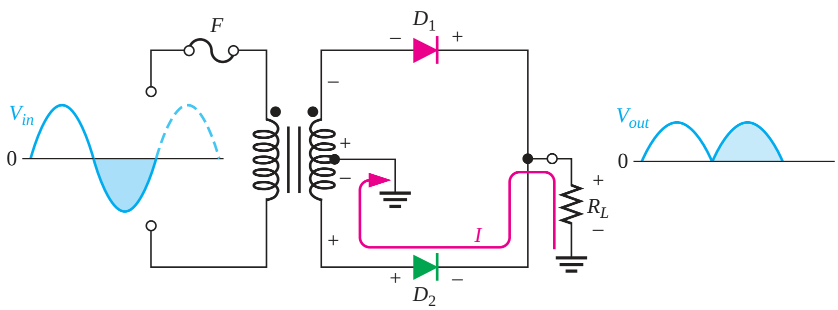
For a positive half-cycle of the input voltage, the polarities of the secondary voltages are as shown in Figure 2–32(a). This condition forward-biases diode D_1 and reverse-biases diode D_2. The current path is through D_1 and the load resistor R_L, as indicated. For a negative half-cycle of the input voltage, the voltage polarities on the secondary are as shown in Figure 2–32(b). This condition reverse-biases D_1 and forward-biases D_2. The current path is through D_2 and R_L, as indicated. Because the output current during both the positive and negative portions of the input cycle is in the same direction through the load, the output voltage developed across the load resistor is a full-wave rectified dc voltage, as shown.

▶ FIGURE 2–32

Basic operation of a center-tapped full-wave rectifier. Note that the current through the load resistor is in the same direction during the entire input cycle, so the output voltage always has the same polarity.



(a) During positive half-cycles, D_1 is forward-biased and D_2 is reverse-biased.



(b) During negative half-cycles, D_2 is forward-biased and D_1 is reverse-biased.

Effect of the Turns Ratio on the Output Voltage If the transformer's turns ratio is 1, the peak value of the rectified output voltage equals half the peak value of the primary input voltage less the barrier potential, as illustrated in Figure 2–33. Half of the primary

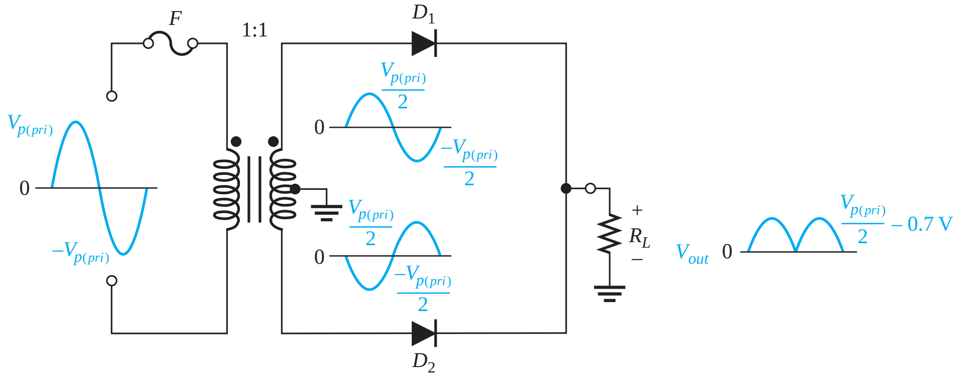


FIGURE 2–33 Center-tapped full-wave rectifier with a transformer turns ratio of 1. $V_{p(pri)}$ is the peak value of the primary voltage.

voltage appears across each half of the secondary winding ($V_{p(sec)} = V_{p(pri)}$). We will begin referring to the forward voltage due to the barrier potential as the **diode drop.**

In order to obtain an output voltage with a peak equal to the input peak (less the diode drop), a step-up transformer with a turns ratio of $n = 2$ must be used, as shown in Figure 2–34. In this case, the total secondary voltage (V_{sec}) is twice the primary voltage ($2V_{pri}$), so the voltage across each half of the secondary is equal to V_{pri}.

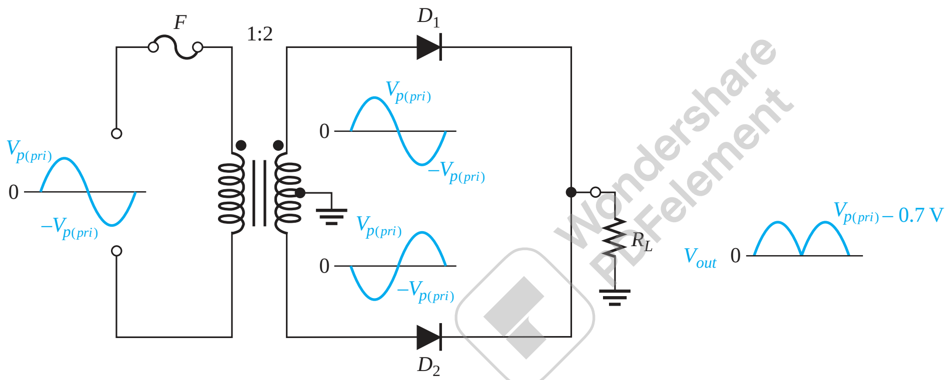


FIGURE 2–34 Center-tapped full-wave rectifier with a transformer turns ratio of 2.

In any case, the output voltage of a center-tapped full-wave rectifier is always one-half of the total secondary voltage less the diode drop, no matter what the turns ratio.

$$V_{out} = \frac{V_{sec}}{2} - 0.7\text{ V}$$

Equation 2–7

Peak Inverse Voltage Each diode in the full-wave rectifier is alternately forward-biased and then reverse-biased. The maximum reverse voltage that each diode must withstand is the peak secondary voltage $V_{p(sec)}$. This is shown in Figure 2–35 where D_2 is assumed to be reverse-biased (red) and D_1 is assumed to be forward-biased (green) to illustrate the concept.

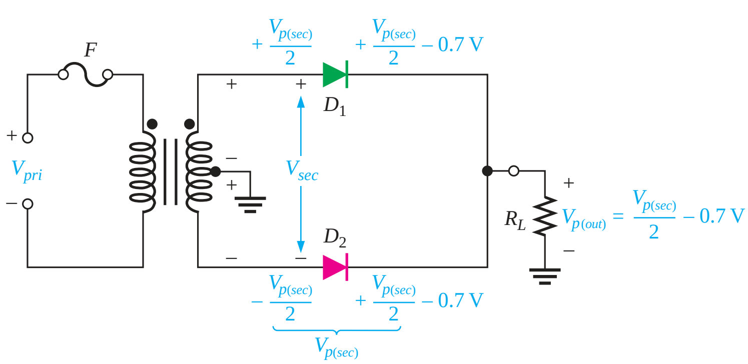


FIGURE 2–35 Diode reverse voltage (D_2 shown reverse-biased and D_1 shown forward-biased).

When the total secondary voltage V_{sec} has the polarity shown, the maximum anode voltage of D_1 is $+V_{p(sec)}/2$ and the maximum anode voltage of D_2 is $-V_{p(sec)}/2$. Since D_1 is assumed to be forward-biased, its cathode is at the same voltage as its anode minus the diode drop; this is also the voltage on the cathode of D_2.

The peak inverse voltage across D_2 is

$$\text{PIV} = \left(\frac{V_{p(sec)}}{2} - 0.7\text{ V}\right) - \left(-\frac{V_{p(sec)}}{2}\right) = \frac{V_{p(sec)}}{2} + \frac{V_{p(sec)}}{2} - 0.7\text{ V}$$
$$= V_{p(sec)} - 0.7\text{ V}$$

Since $V_{p(out)} = V_{p(sec)}/2 - 0.7$ V, then by multiplying each term by 2 and transposing,

$$V_{p(sec)} = 2V_{p(out)} + 1.4\text{ V}$$

Therefore, by substitution, the peak inverse voltage across either diode in a full-wave center-tapped rectifier is

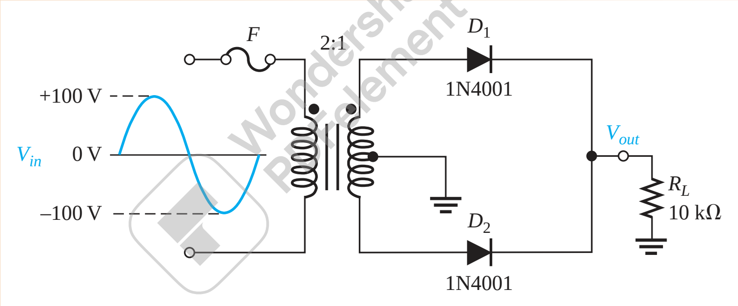
Equation 2–8
$$\mathbf{PIV = 2V_{p(out)} + 0.7\ V}$$

EXAMPLE 2–6

(a) Show the voltage waveforms across each half of the secondary winding and across R_L when a 100 V peak sine wave is applied to the primary winding in Figure 2–36.

(b) What minimum PIV rating must the diodes have?

▶ FIGURE 2–36



Solution

(a) The transformer turns ratio $n = 0.5$. The total peak secondary voltage is

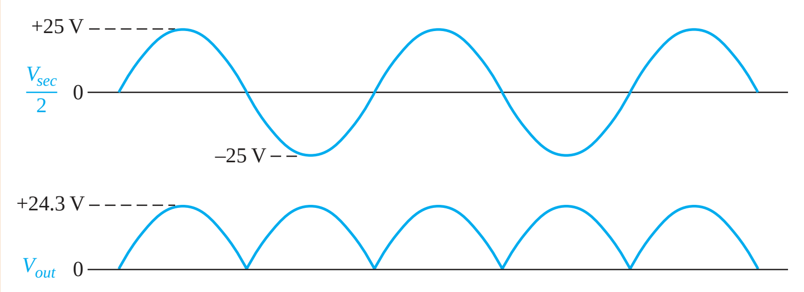
$$V_{p(sec)} = nV_{p(pri)} = 0.5(100\text{ V}) = 50\text{ V}$$

There is a 25 V peak across each half of the secondary with respect to ground. The output load voltage has a peak value of 25 V, less the 0.7 V drop across the diode. The waveforms are shown in Figure 2–37.

(b) Each diode must have a minimum PIV rating of

$$\text{PIV} = 2V_{p(out)} + 0.7\text{ V} = 2(24.3\text{ V}) + 0.7\text{ V} = \mathbf{49.3\ V}$$

▶ FIGURE 2–37



Related Problem What diode PIV rating is required to handle a peak input of 160 V in Figure 2–36?

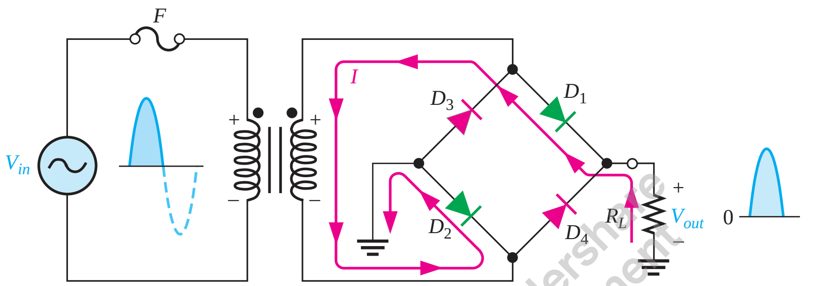
Open the Multisim file E02-06 in the Examples folder on the companion website. For the specified input voltage, measure the voltage waveforms across each half of the secondary and across the load resistor. Compare with the results shown in the example.

Bridge Full-Wave Rectifier Operation

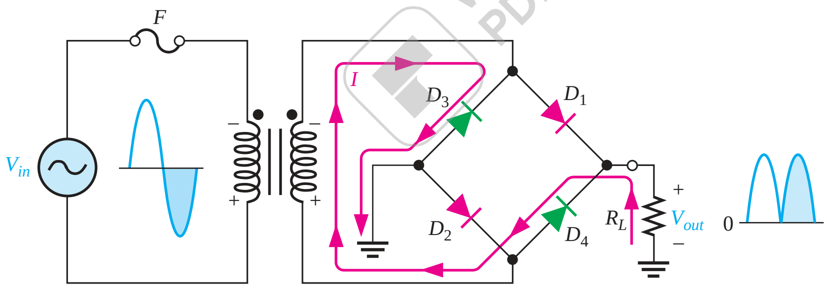
The **bridge rectifier** uses four diodes connected as shown in Figure 2–38. When the input cycle is positive as in part (a), diodes D_1 and D_2 are forward-biased and conduct current in the direction shown. A voltage is developed across R_L that looks like the positive half of the input cycle. During this time, diodes D_3 and D_4 are reverse-biased.

◀ FIGURE 2–38

Operation of a bridge rectifier.



(a) During the positive half-cycle of the input, D_1 and D_2 are forward-biased and conduct current. D_3 and D_4 are reverse-biased.



(b) During the negative half-cycle of the input, D_3 and D_4 are forward-biased and conduct current. D_1 and D_2 are reverse-biased.

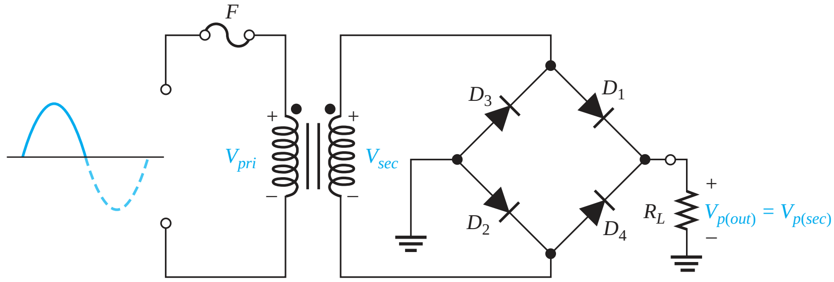
When the input cycle is negative as in Figure 2–38(b), diodes D_3 and D_4 are forward-biased and conduct current in the same direction through R_L as during the positive half-cycle. During the negative half-cycle, D_1 and D_2 are reverse-biased. A full-wave rectified output voltage appears across R_L as a result of this action.

Bridge Output Voltage A bridge rectifier with a transformer-coupled input is shown in Figure 2–39(a). During the positive half-cycle of the total secondary voltage, diodes D_1 and D_2 are forward-biased. Neglecting the diode drops, the secondary voltage appears across the load resistor. The same is true when D_3 and D_4 are forward-biased during the negative half-cycle.

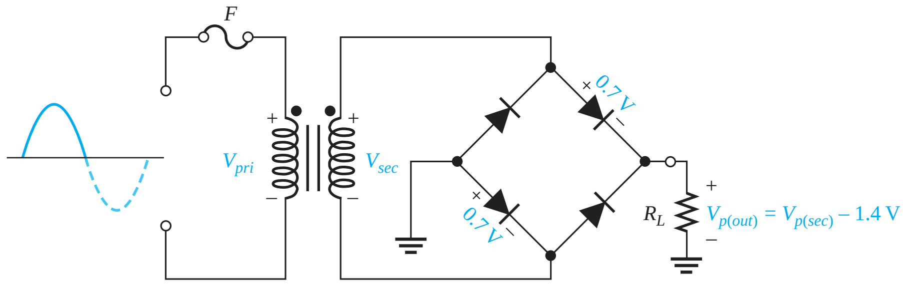
$$V_{p(out)} = V_{p(sec)}$$

As you can see in Figure 2–39(b), two diodes are always in series with the load resistor during both the positive and negative half-cycles. If these diode drops are taken into account, the output voltage is

$$\mathbf{V_{p(out)} = V_{p(sec)} - 1.4\ V} \qquad \text{Equation 2–9}$$



(a) Ideal diodes



(b) Practical diodes (Diode drops included)

▲ FIGURE 2–39

Bridge operation during a positive half-cycle of the primary and secondary voltages.

Peak Inverse Voltage Let's assume that D_1 and D_2 are forward-biased and examine the reverse voltage across D_3 and D_4. Visualizing D_1 and D_2 as shorts (ideal model), as in Figure 2–40(a), you can see that D_3 and D_4 have a peak inverse voltage equal to the peak secondary voltage. Since the output voltage is *ideally* equal to the secondary voltage,

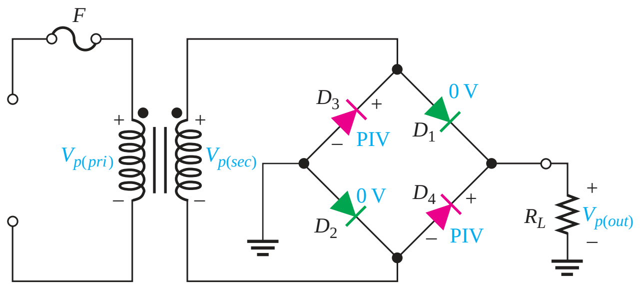
$$\text{PIV} = V_{p(out)}$$

If the diode drops of the forward-biased diodes are included as shown in Figure 2–40(b), the peak inverse voltage across each reverse-biased diode in terms of $V_{p(out)}$ is

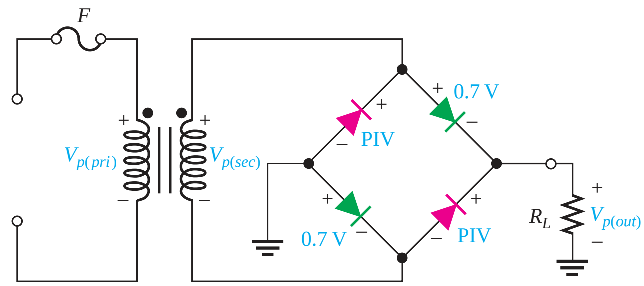
Equation 2–10

$$\textbf{PIV} = \boldsymbol{V_{p(out)}} + \textbf{0.7 V}$$

The PIV rating of the bridge diodes is less than that required for the center-tapped configuration. If the diode drop is neglected, the bridge rectifier requires diodes with half the PIV rating of those in a center-tapped rectifier for the same output voltage.



(a) For the ideal diode model (forward-biased diodes D_1 and D_2 are shown in green), PIV = $V_{p(out)}$.



(b) For the practical diode model (forward-biased diodes D_1 and D_2 are shown in green), PIV = $V_{p(out)}$ + 0.7 V.

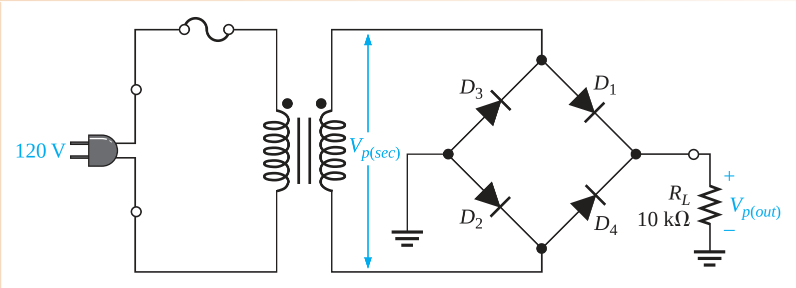
▲ FIGURE 2–40

Peak inverse voltages across diodes D_3 and D_4 in a bridge rectifier during the positive half-cycle of the secondary voltage.

EXAMPLE 2–7

Determine the peak output voltage for the bridge rectifier in Figure 2–41. Assuming the practical model, what PIV rating is required for the diodes? The transformer is specified to have a 12 V rms secondary voltage for the standard 120 V across the primary.

▶ FIGURE 2–41



Solution The peak output voltage (taking into account the two diode drops) is

$$V_{p(sec)} = 1.414V_{rms} = 1.414(12\text{ V}) \cong 17\text{ V}$$
$$V_{p(out)} = V_{p(sec)} - 1.4\text{ V} = 17\text{ V} - 1.4\text{ V} = \mathbf{15.6\text{ V}}$$

The PIV rating for each diode is

$$\text{PIV} = V_{p(out)} + 0.7\text{ V} = 15.6\text{ V} + 0.7\text{ V} = \mathbf{16.3\text{ V}}$$

Related Problem Determine the peak output voltage for the bridge rectifier in Figure 2–41 if the transformer produces an rms secondary voltage of 30 V. What is the PIV rating for the diodes?

Open the Multisim file E02-07 in the Examples folder on the companion website. Measure the output voltage and compare to the calculated value.

SECTION 2–5 CHECKUP

1. How does a full-wave voltage differ from a half-wave voltage?
2. What is the average value of a full-wave rectified voltage with a peak value of 60 V?
3. Which type of full-wave rectifier has the greater output voltage for the same input voltage and transformer turns ratio?
4. For a peak output voltage of 45 V, in which type of rectifier would you use diodes with a PIV rating of 50 V?
5. What PIV rating is required for diodes used in the type of rectifier that was not selected in Question 4?

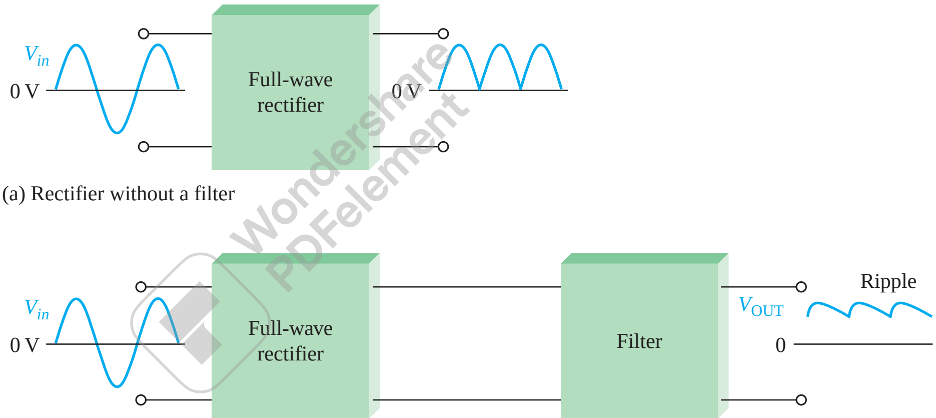
2–6 POWER SUPPLY FILTERS AND REGULATORS

A power supply filter ideally eliminates the fluctuations in the output voltage of a half-wave or full-wave rectifier and produces a constant-level dc voltage. Filtering is necessary because electronic circuits require a constant source of dc voltage and current to provide power and biasing for proper operation. Filters are implemented with capacitors, as you will see in this section. Voltage regulation in power supplies is usually done with integrated circuit voltage regulators. A voltage regulator prevents changes in the filtered dc voltage due to variations in input voltage or load.

After completing this section, you should be able to

- **Explain and analyze power supply filters and regulators**
- Describe the operation of a capacitor-input filter
  ◆ Define *ripple voltage* ◆ Calculate the ripple factor ◆ Calculate the output voltage of a filtered full-wave rectifier ◆ Discuss surge current
- Discuss voltage regulators
  ◆ Calculate the line regulation ◆ Calculate the load regulation

In most power supply applications, the standard 60 Hz ac power line voltage must be converted to an approximately constant dc voltage. The 60 Hz pulsating dc output of a half-wave rectifier or the 120 Hz pulsating output of a full-wave rectifier must be filtered to reduce the large voltage variations. Figure 2–42 illustrates the filtering concept showing a nearly smooth dc output voltage from the filter. The small amount of fluctuation in the filter output voltage is called *ripple.*



(a) Rectifier without a filter

(b) Rectifier with a filter (output ripple is exaggerated)

▲ **FIGURE 2–42**

Power supply filtering.

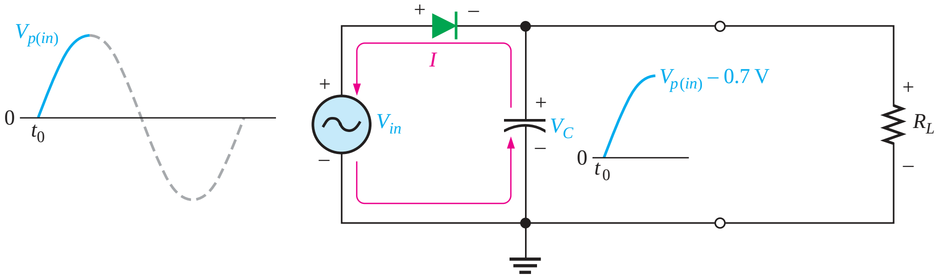
Capacitor-Input Filter

A half-wave rectifier with a capacitor-input filter is shown in Figure 2–43. The filter is simply a capacitor connected from the rectifier output to ground. R_L represents the equivalent resistance of a load. We will use the half-wave rectifier to illustrate the basic principle and then expand the concept to full-wave rectification.

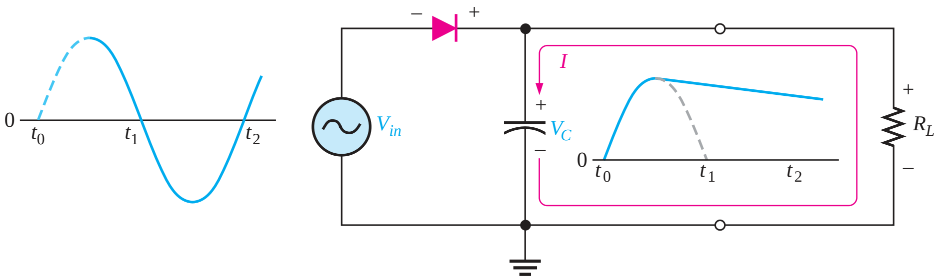
During the positive first quarter-cycle of the input, the diode is forward-biased, allowing the capacitor to charge to within 0.7 V of the input peak, as illustrated in Figure 2–43(a). When the input begins to decrease below its peak, as shown in part (b), the capacitor retains its charge and the diode becomes reverse-biased because the cathode is more positive than the anode. During the remaining part of the cycle, the capacitor can discharge only through the load resistance at a rate determined by the R_LC time constant, which is normally long compared to the period of the input. The larger the time constant, the less the capacitor will discharge. During the first quarter of the next cycle, as illustrated in part (c), the diode will again become forward-biased when the input voltage exceeds the capacitor voltage by approximately 0.7 V.

SAFETY NOTE

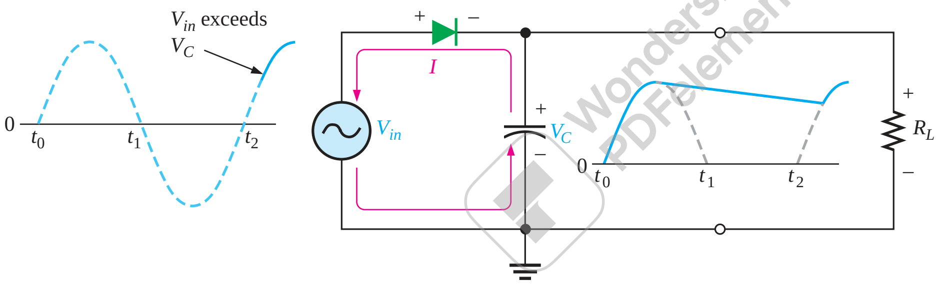
When installing polarized capacitors in a circuit, be sure to observe the proper polarity. The positive lead always connects to the more positive side of the circuit. An incorrectly connected polarized capacitor can explode.



(a) Initial charging of the capacitor (diode is forward-biased) happens only once when power is turned on.



(b) The capacitor discharges through R_L after peak of positive alternation when the diode is reverse-biased. This discharging occurs during the portion of the input voltage indicated by the solid dark blue curve.

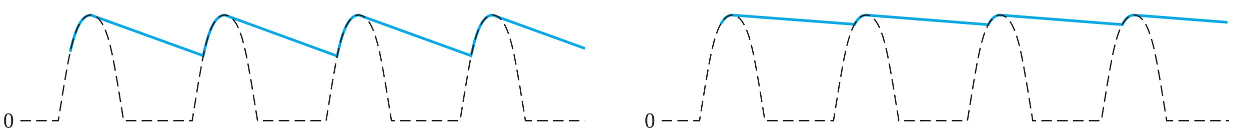


(c) The capacitor charges back to peak of input when the diode becomes forward-biased. This charging occurs during the portion of the input voltage indicated by the solid dark blue curve.

▲ **FIGURE 2–43**

Operation of a half-wave rectifier with a capacitor-input filter. The current indicates charging or discharging of the capacitor.

Ripple Voltage As you have seen, the capacitor quickly charges at the beginning of a cycle and slowly discharges through R_L after the positive peak of the input voltage (when the diode is reverse-biased). The variation in the capacitor voltage due to the charging and discharging is called the **ripple voltage**. Generally, ripple is undesirable; thus, the smaller the ripple, the better the filtering action, as illustrated in Figure 2–44.



(a) Larger ripple (blue) means less effective filtering.

(b) Smaller ripple means more effective filtering. Generally, the larger the capacitor value, the smaller the ripple for the same input and load.

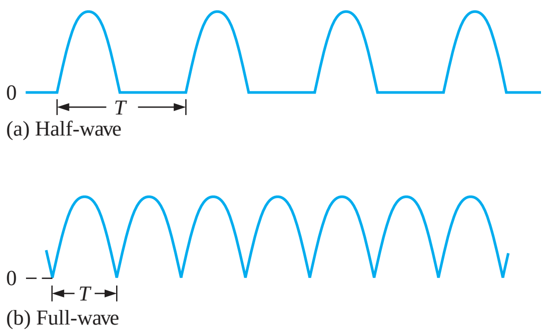
▲ **FIGURE 2–44**

Half-wave ripple voltage (blue line).

For a given input frequency, the output frequency of a full-wave rectifier is twice that of a half-wave rectifier, as illustrated in Figure 2–45. This makes a full-wave rectifier easier to filter because of the shorter time between peaks. When filtered, the full-wave rectified voltage has a smaller ripple than does a half-wave voltage for the same load resistance and capacitor values. The capacitor discharges less during the shorter interval between full-wave pulses, as shown in Figure 2–46.

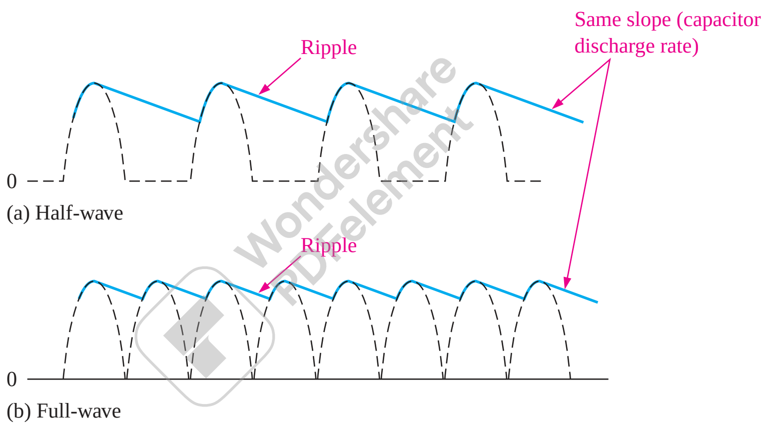
▶ FIGURE 2–45

The period of a full-wave rectified voltage is half that of a half-wave rectified voltage. The output frequency of a full-wave rectifier is twice that of a half-wave rectifier.



▶ FIGURE 2–46

Comparison of ripple voltages for half-wave and full-wave rectified voltages with the same filter capacitor and load and derived from the same sinusoidal input voltage.



Ripple Factor The **ripple factor (*r*)** is an indication of the effectiveness of the filter and is defined as

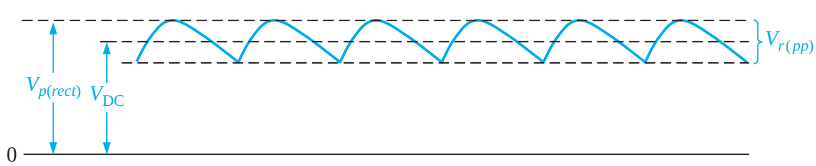
Equation 2–11

$$r = \frac{V_{r(pp)}}{V_{DC}}$$

where $V_{r(pp)}$ is the peak-to-peak ripple voltage and V_{DC} is the dc (average) value of the filter's output voltage, as illustrated in Figure 2–47. The lower the ripple factor, the better the filter. The ripple factor can be lowered by increasing the value of the filter capacitor or increasing the load resistance.

▶ FIGURE 2–47

V_r and V_{DC} determine the ripple factor.



For a full-wave rectifier with a capacitor-input filter, approximations for the peak-to-peak ripple voltage, $V_{r(pp)}$, and the dc value of the filter output voltage, V_{DC}, are given in the following equations. The variable $V_{p(rect)}$ is the unfiltered peak rectified voltage. Notice that if R_L or C increases, the ripple voltage decreases and the dc voltage increases.

$$V_{r(pp)} \cong \left(\frac{1}{fR_LC}\right)V_{p(rect)}$$ **Equation 2–12**

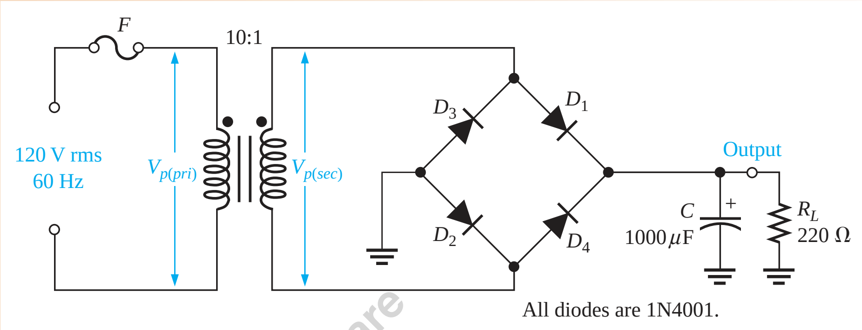
$$V_{DC} \cong \left(1 - \frac{1}{2fR_LC}\right)V_{p(rect)}$$ **Equation 2–13**

The derivations for these equations can be found in "Derivations of Selected Equations" at www.pearsonhighered.com/floyd.

EXAMPLE 2–8

Determine the ripple factor for the filtered bridge rectifier with a load as indicated in Figure 2–48.

▶ FIGURE 2–48



Solution The transformer turns ratio is $n = 0.1$. The peak primary voltage is

$$V_{p(pri)} = 1.414V_{rms} = 1.414(120\text{ V}) = 170\text{ V}$$

The peak secondary voltage is

$$V_{p(sec)} = nV_{p(pri)} = 0.1(170\text{ V}) = 17.0\text{ V}$$

The unfiltered peak full-wave rectified voltage is

$$V_{p(rect)} = V_{p(sec)} - 1.4\text{ V} = 17.0\text{ V} - 1.4\text{ V} = 15.6\text{ V}$$

The frequency of a full-wave rectified voltage is 120 Hz. The approximate peak-to-peak ripple voltage at the output is

$$V_{r(pp)} \cong \left(\frac{1}{fR_LC}\right)V_{p(rect)} = \left(\frac{1}{(120\text{ Hz})(220\ \Omega)(1000\ \mu\text{F})}\right)15.6\text{ V} = 0.591\text{ V}$$

The approximate dc value of the output voltage is determined as follows:

$$V_{DC} = \left(1 - \frac{1}{2fR_LC}\right)V_{p(rect)} = \left(1 - \frac{1}{(240\text{ Hz})(220\ \Omega)(1000\ \mu\text{F})}\right)15.6\text{ V} = 15.3\text{ V}$$

The resulting ripple factor is

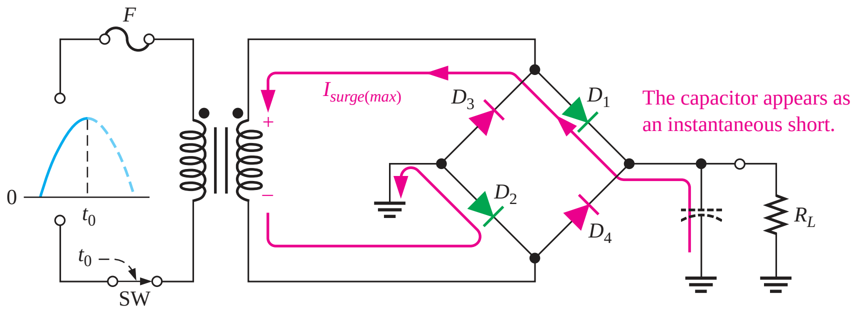
$$r = \frac{V_{r(pp)}}{V_{DC}} = \frac{0.591\text{ V}}{15.3\text{ V}} = \mathbf{0.039}$$

The percent ripple is 3.9%.

Related Problem Determine the peak-to-peak ripple voltage if the filter capacitor in Figure 2–48 is increased to 2200 μF and the load resistance changes to 2.2 kΩ.

Open the Multisim file E02-08 in the Examples folder on the companion website. For the specified input voltage, measure the peak-to-peak ripple voltage and the dc value at the output. Do the results agree closely with the calculated values? If not, can you explain why?

Surge Current in the Capacitor-Input Filter Before the switch in Figure 2–49 is closed, the filter capacitor is uncharged. At the instant the switch is closed, voltage is connected to the bridge and the uncharged capacitor appears as a short, as shown. This produces an initial surge of current, I_{surge}, through the two forward-biased diodes D_1 and D_2. The worst-case situation occurs when the switch is closed at a peak of the secondary voltage and a maximum surge current, $I_{surge(max)}$, is produced, as illustrated in the figure.



▶ FIGURE 2–49

Surge current in a capacitor-input filter.

In dc power supplies, a **fuse** is always placed in the primary circuit of the transformer, as shown in Figure 2–49. A slow-blow type fuse is generally used because of the surge current that initially occurs when power is first turned on. The fuse rating is determined by calculating the power in the power supply load, which is the output power. Since $P_{in} = P_{out}$ in an ideal transformer, the primary current can be calculated as

$$I_{pri} = \frac{P_{in}}{120\text{ V}}$$

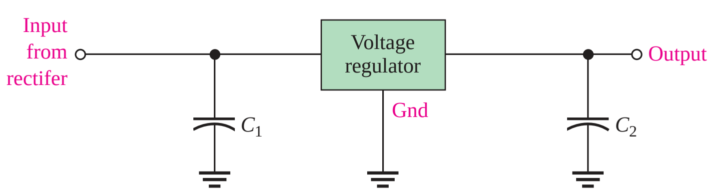
The fuse rating should be at least 20% larger than the calculated value of I_{pri}.

Voltage Regulators

While filters can reduce the ripple from power supplies to a low value, the most effective approach is a combination of a capacitor-input filter used with a voltage regulator. A voltage regulator is connected to the output of a filtered rectifier and maintains a constant output voltage (or current) despite changes in the input, the load current, or the temperature. The capacitor-input filter reduces the input ripple to the regulator to an acceptable level. The combination of a large capacitor and a voltage regulator helps produce an excellent power supply.

Most regulators are integrated circuits and have three terminals—an input terminal, an output terminal, and a reference (or adjust) terminal. The input to the regulator is first filtered with a capacitor to reduce the ripple to <10%. The regulator reduces the ripple to a negligible amount. In addition, most regulators have an internal voltage reference, short-circuit protection, and thermal shutdown circuitry. They are available in a variety of voltages, including positive and negative outputs, and can be designed for variable outputs with a minimum of external components. Typically, voltage regulators can furnish a constant output of one or more amps of current with high ripple rejection.

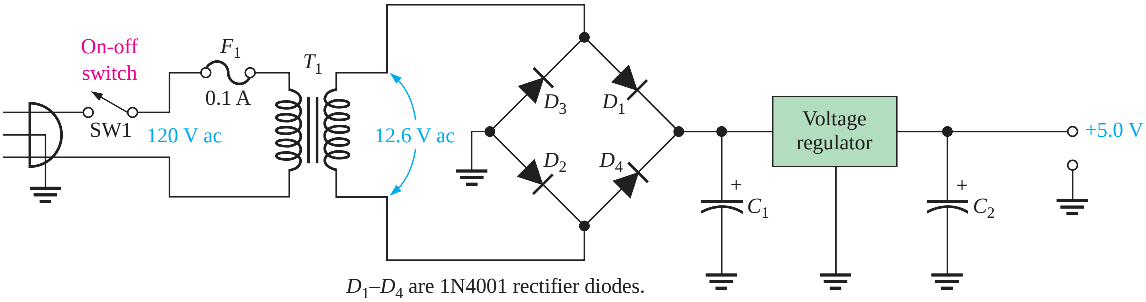
Three-terminal regulators designed for fixed output voltages require only external capacitors to complete the regulation portion of the power supply, as shown in Figure 2–50. Filtering is accomplished by a large-value capacitor between the input voltage and ground. An output capacitor (typically 0.1 μF to 1.0 μF) is connected from the output to ground to improve the transient response.



▶ FIGURE 2–50

A voltage regulator with input and output capacitors.

A basic fixed power supply with a +5 V voltage regulator is shown in Figure 2–51. Specific integrated circuit three-terminal regulators with fixed output voltages are covered in Chapter 17.



▲ FIGURE 2–51

A basic +5.0 V regulated power supply.

Percent Regulation

The regulation expressed as a percentage is a figure of merit used to specify the performance of a voltage regulator. It can be in terms of input (line) regulation or load regulation.

Line Regulation The **line regulation** specifies how much change occurs in the output voltage for a given change in the input voltage. It is typically defined as a ratio of a change in output voltage for a corresponding change in the input voltage expressed as a percentage.

$$\textbf{Line regulation} = \left(\frac{\Delta V_{OUT}}{\Delta V_{IN}}\right)100\% \qquad \text{Equation 2–14}$$

Load Regulation The **load regulation** specifies how much change occurs in the output voltage over a certain range of load current values, usually from minimum current (no load, NL) to maximum current (full load, FL). It is normally expressed as a percentage and can be calculated with the following formula:

$$\textbf{Load regulation} = \left(\frac{V_{NL} - V_{FL}}{V_{FL}}\right)100\% \qquad \text{Equation 2–15}$$

where V_{NL} is the output voltage with no load and V_{FL} is the output voltage with full (maximum) load.

EXAMPLE 2–9

A certain 7805 regulator has a measured no-load output voltage of 5.18 V and a full-load output of 5.15 V. What is the load regulation expressed as a percentage?

Solution

$$\text{Load regulation} = \left(\frac{V_{NL} - V_{FL}}{V_{FL}}\right)100\% = \left(\frac{5.18\text{ V} - 5.15\text{ V}}{5.15\text{ V}}\right)100\% = \mathbf{0.58\%}$$

Related Problem

If the no-load output voltage of a regulator is 24.8 V and the full-load output is 23.9 V, what is the load regulation expressed as a percentage?

SECTION 2–6 CHECKUP

1. When a 60 Hz sinusoidal voltage is applied to the input of a half-wave rectifier, what is the output frequency?
2. When a 60 Hz sinusoidal voltage is applied to the input of a full-wave rectifier, what is the output frequency?

3. What causes the ripple voltage on the output of a capacitor-input filter?
4. If the load resistance connected to a filtered power supply is decreased, what happens to the ripple voltage?
5. Define *ripple factor.*
6. What is the difference between input (line) regulation and load regulation?

2–7 DIODE LIMITERS AND CLAMPERS

Diode circuits, called limiters or clippers, are sometimes used to clip off portions of signal voltages above or below certain levels. Another type of diode circuit, called a clamper, is used to add or restore a dc level to an electrical signal. Both limiter and clamper diode circuits will be examined in this section.

After completing this section, you should be able to

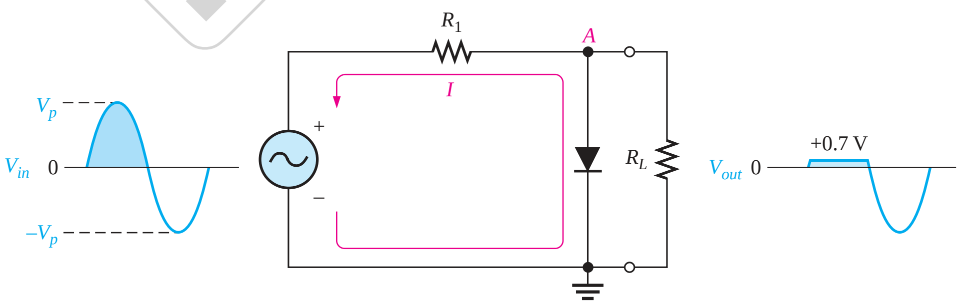
- **Explain and analyze the operation of diode limiters and clampers**
- Describe the operation of a diode limiter
  - Discuss biased limiters ◆ Discuss voltage-divider bias ◆ Describe an application
- Describe the operation of a diode clamper

Diode Limiters

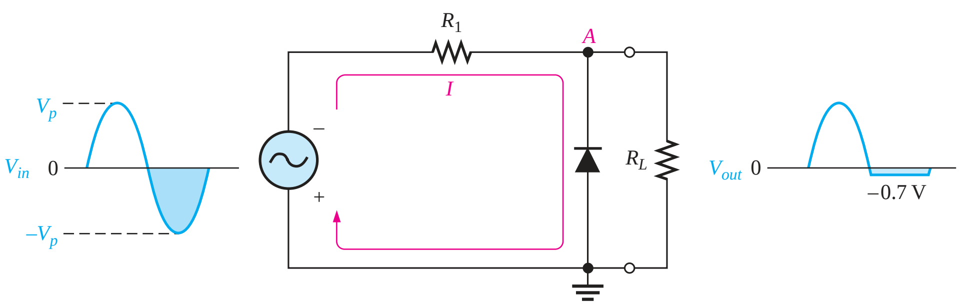
Figure 2–52(a) shows a diode positive **limiter** (also called **clipper**) that limits or clips the positive part of the input voltage. As the input voltage goes positive, the diode becomes forward-biased and conducts current. Point A is limited to $+0.7$ V when the input voltage exceeds this

▶ FIGURE 2–52

Examples of diode limiters (clippers).



(a) Limiting of the positive alternation. The diode is forward-biased during the positive alternation (above 0.7 V) and reverse-biased during the negative alternation.



(b) Limiting of the negative alternation. The diode is forward-biased during the negative alternation (below −0.7 V) and reverse-biased during the positive alternation.

value. When the input voltage goes back below 0.7 V, the diode is reverse-biased and appears as an open. The output voltage looks like the negative part of the input voltage, but with a magnitude determined by the voltage divider formed by R_1 and the load resistor, R_L, as follows:

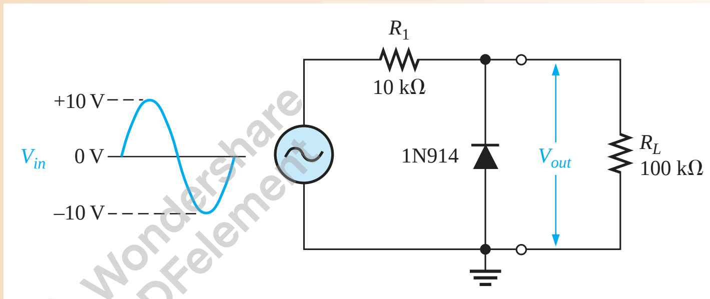
$$V_{out} = \left(\frac{R_L}{R_1 + R_L}\right)V_{in}$$

If R_1 is small compared to R_L, then $V_{out} \cong V_{in}$.

If the diode is turned around, as in Figure 2–52(b), the negative part of the input voltage is clipped off. When the diode is forward-biased during the negative part of the input voltage, point A is held at -0.7 V by the diode drop. When the input voltage goes above -0.7 V, the diode is no longer forward-biased; and a voltage appears across R_L proportional to the input voltage.

EXAMPLE 2–10

What would you expect to see displayed on an oscilloscope connected across R_L in the limiter shown in Figure 2–53?

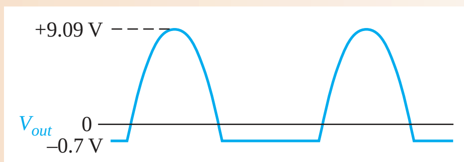


▶ FIGURE 2–53

Solution The diode is forward-biased and conducts when the input voltage goes below -0.7 V. So, for the negative limiter, determine the peak output voltage across R_L by the following equation:

$$V_{p(out)} = \left(\frac{R_L}{R_1 + R_L}\right)V_{p(in)} = \left(\frac{100\text{ k}\Omega}{110\text{ k}\Omega}\right)10\text{ V} = 9.09\text{ V}$$

The scope will display an output waveform as shown in Figure 2–54.



▶ FIGURE 2–54

Output voltage waveform for Figure 2–53.

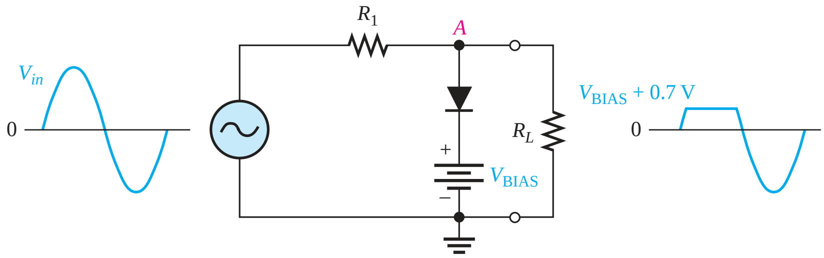
Related Problem Describe the output waveform for Figure 2–53 if R_1 is changed to 1 kΩ.

Open the Multisim file E02-10 in the Examples folder on the companion website. For the specified input, measure the resulting output waveform. Compare with the waveform shown in the example.

Biased Limiters The level to which an ac voltage is limited can be adjusted by adding a bias voltage, V_{BIAS}, in series with the diode, as shown in Figure 2–55. The voltage at point A must equal $V_{BIAS} + 0.7$ V before the diode will become forward-biased and conduct. Once the diode begins to conduct, the voltage at point A is limited to $V_{BIAS} + 0.7$ V so that all input voltage above this level is clipped off.

▶ **FIGURE 2–55**

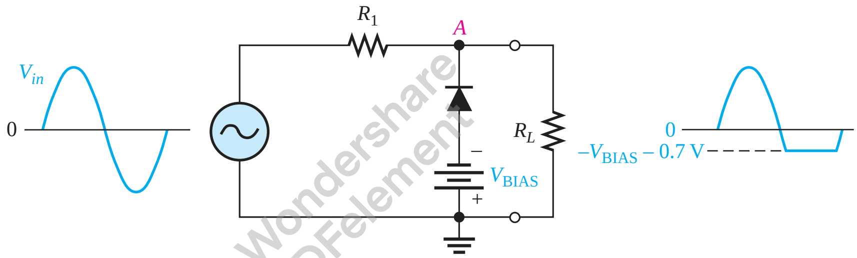
A positive limiter.



To limit a voltage to a specified negative level, the diode and bias voltage must be connected as in Figure 2–56. In this case, the voltage at point A must go below $-V_{BIAS} - 0.7$ V to forward-bias the diode and initiate limiting action as shown.

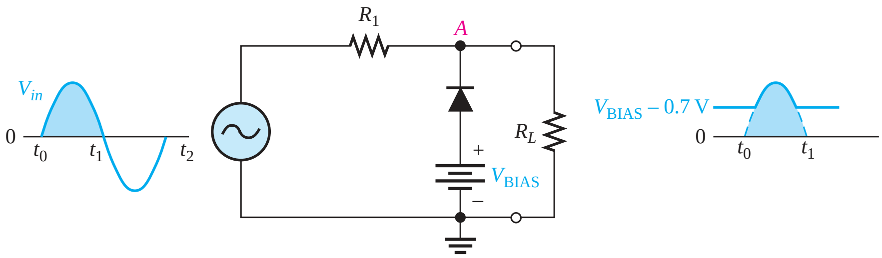
▶ **FIGURE 2–56**

A negative limiter.

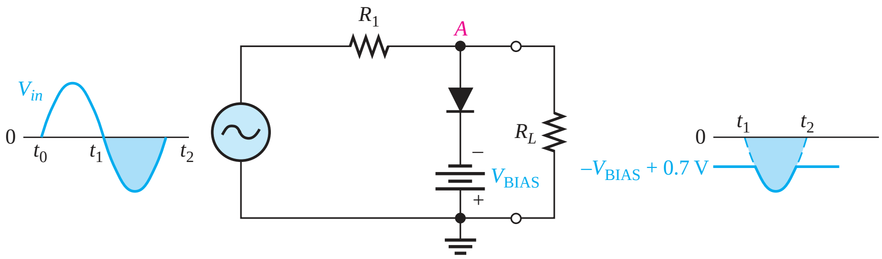


By turning the diode around, the positive limiter can be modified to limit the output voltage to the portion of the input voltage waveform above $V_{BIAS} - 0.7$ V, as shown by the output waveform in Figure 2–57(a). Similarly, the negative limiter can be modified to limit the output voltage to the portion of the input voltage waveform below $-V_{BIAS} + 0.7$ V, as shown by the output waveform in part (b).

▶ **FIGURE 2–57**



(a)

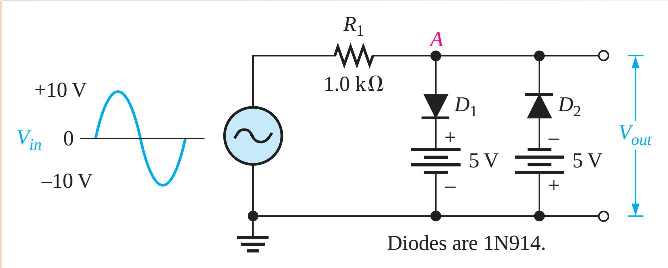


(b)

EXAMPLE 2–11

Figure 2–58 shows a circuit combining a positive limiter with a negative limiter. Determine the output voltage waveform.

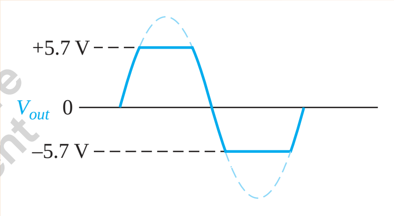
▶ **FIGURE 2–58**



Solution When the voltage at point A reaches +5.7 V, diode D_1 conducts and limits the waveform to +5.7 V. Diode D_2 does not conduct until the voltage reaches −5.7 V. Therefore, positive voltages above +5.7 V and negative voltages below −5.7 V are clipped off. The resulting output voltage waveform is shown in Figure 2–59.

▶ **FIGURE 2–59**

Output voltage waveform for Figure 2–58.



Related Problem Determine the output voltage waveform in Figure 2–58 if both dc sources are 10 V and the input voltage has a peak value of 20 V.

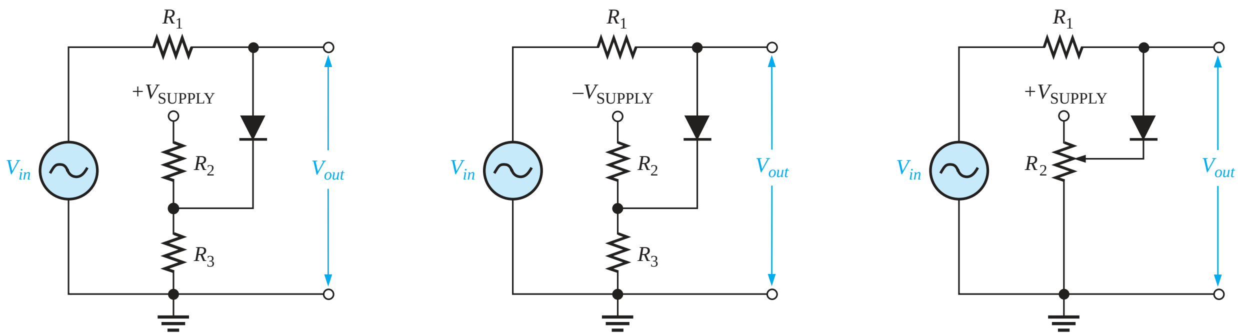
Open the Multisim file E02-11 in the Examples folder on the companion website. For the specified input, measure the resulting output waveform. Compare with the waveform shown in the example.

Voltage-Divider Bias The bias voltage sources that have been used to illustrate the basic operation of diode limiters can be replaced by a resistive voltage divider that derives the desired bias voltage from the dc supply voltage, as shown in Figure 2–60. The bias voltage is set by the resistor values according to the voltage-divider formula.

$$V_{BIAS} = \left(\frac{R_3}{R_2 + R_3}\right)V_{SUPPLY}$$

A positively biased limiter is shown in Figure 2–60(a), a negatively biased limiter is shown in part (b), and a variable positive bias circuit using a potentiometer voltage divider is shown in part (c). The bias resistors must be small compared to R_1 so that the forward current through the diode will not affect the bias voltage.

A Limiter Application Many circuits have certain restrictions on the input level to avoid damaging the circuit. For example, almost all digital circuits should not have an input level that exceeds the power supply voltage. An input of a few volts more than this could damage the circuit. To prevent the input from exceeding a specific level, you may see a diode limiter across the input signal path in many digital circuits.



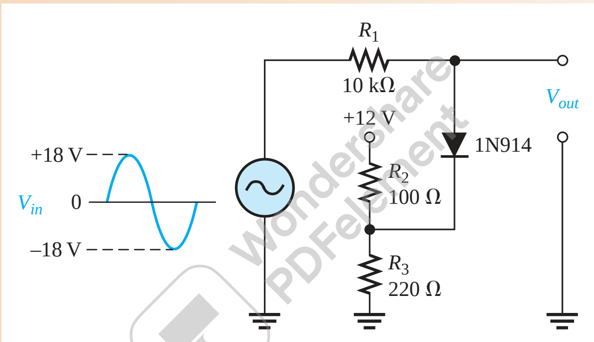
(a) Positive limiter (b) Negative limiter (c) Variable positive limiter

▲ **FIGURE 2–60**

Diode limiters implemented with voltage-divider bias.

EXAMPLE 2–12 Describe the output voltage waveform for the diode limiter in Figure 2–61.

▶ **FIGURE 2–61**

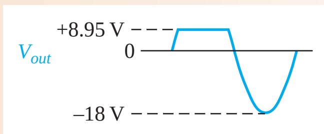


Solution The circuit is a positive limiter. Use the voltage-divider formula to determine the bias voltage.

$$V_{BIAS} = \left(\frac{R_3}{R_2 + R_3}\right)V_{SUPPLY} = \left(\frac{220\ \Omega}{100\ \Omega + 220\ \Omega}\right)12\text{ V} = 8.25\text{ V}$$

The output voltage waveform is shown in Figure 2–62. The positive part of the output voltage waveform is limited to $V_{BIAS} + 0.7$ V.

▶ **FIGURE 2–62**



Related Problem How would you change the voltage divider in Figure 2–61 to limit the output voltage to +6.7 V?

Open the Multisim file E02-12 in the Examples folder on the companion website. Observe the output voltage on the oscilloscope and compare to the calculated result.

Diode Clampers

A clamper adds a dc level to an ac voltage. **Clampers** are sometimes known as *dc restorers*. Figure 2–63 shows a diode clamper that inserts a positive dc level in the output waveform. The operation of this circuit can be seen by considering the first negative half-cycle of the input voltage. When the input voltage initially goes negative, the diode is forward-biased, allowing the capacitor to charge to near the peak of the input ($V_{p(in)} - 0.7$ V), as shown in Figure 2–63(a). Just after the negative peak, the diode is reverse-biased. This is because the cathode is held near $V_{p(in)} - 0.7$ V by the charge on the capacitor. The capacitor can only discharge through the high resistance of R_L. So, from the peak of one negative half-cycle to the next, the capacitor discharges very little. The amount that is discharged, of course, depends on the value of R_L.

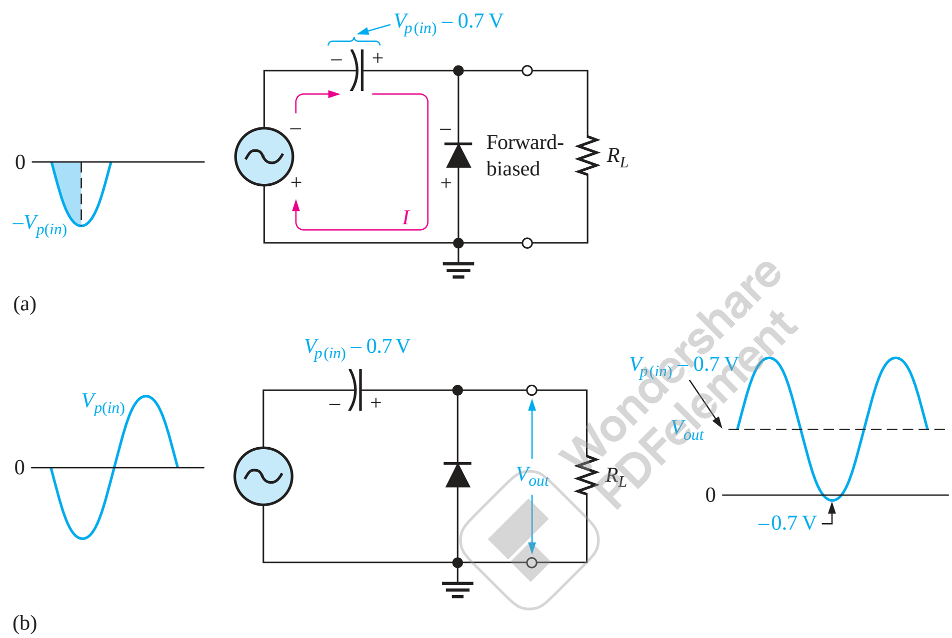


FIGURE 2–63

Positive clamper operation.

If the capacitor discharges during the period of the input wave, clamping action is affected. If the *RC* time constant is 100 times the period, the clamping action is excellent. An *RC* time constant of ten times the period will have a small amount of distortion at the ground level due to the charging current.

The net effect of the clamping action is that the capacitor retains a charge approximately equal to the peak value of the input less the diode drop. The capacitor voltage acts essentially as a battery in series with the input voltage. The dc voltage of the capacitor adds to the input voltage by superposition, as in Figure 2–63(b).

If the diode is turned around, a negative dc voltage is added to the input voltage to produce the output voltage as shown in Figure 2–64.

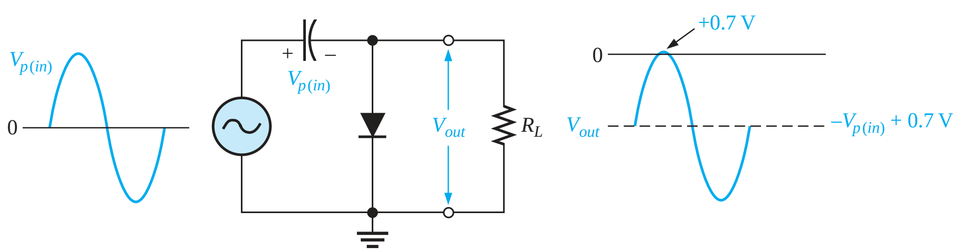


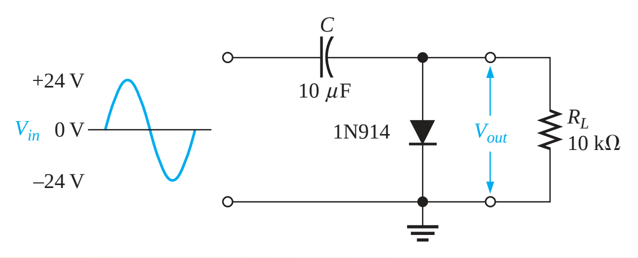
FIGURE 2–64

Negative clamper.

EXAMPLE 2–13

What is the output voltage that you would expect to observe across R_L in the clamping circuit of Figure 2–65? Assume that RC is large enough to prevent significant capacitor discharge.

▶ FIGURE 2–65



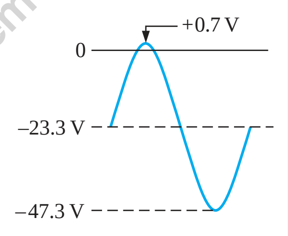
Solution Ideally, a negative dc value equal to the input peak less the diode drop is inserted by the clamping circuit.

$$V_{DC} \cong -(V_{p(in)} - 0.7\text{ V}) = -(24\text{ V} - 0.7\text{ V}) = \mathbf{-23.3\text{ V}}$$

Actually, the capacitor will discharge slightly between peaks, and, as a result, the output voltage will have an average value of slightly less than that calculated above. The output waveform goes to approximately +0.7 V, as shown in Figure 2–66.

▶ FIGURE 2–66

Output waveform across R_L for Figure 2–65.



Related Problem What is the output voltage that you would observe across R_L in Figure 2–65 for $C = 22\ \mu\text{F}$ and $R_L = 18\text{ k}\Omega$?

Open the Multisim file E02-13 in the Examples folder on the companion website. For the specified input, measure the output waveform. Compare with the waveform shown in the example.

SECTION 2–7 CHECKUP

1. Discuss how diode limiters and diode clampers differ in terms of their function.
2. What is the difference between a positive limiter and a negative limiter?
3. What is the maximum voltage across an unbiased positive silicon diode limiter during the positive alternation of the input voltage?
4. To limit the output voltage of a positive limiter to 5 V when a 10 V peak input is applied, what value must the bias voltage be?
5. What component in a clamping circuit effectively acts as a battery?

2–8 VOLTAGE MULTIPLIERS

Voltage multipliers use clamping action to increase peak rectified voltages without the necessity of increasing the transformer's voltage rating. Multiplication factors of two, three, and four are common. Voltage multipliers are used in high-voltage, low-current applications such as cathode-ray tubes (CRTs) and particle accelerators.

After completing this section, you should be able to

- **Explain and analyze the operation of diode voltage multipliers**
- Discuss voltage doublers
  - Explain the half-wave voltage doubler
  - Explain the full-wave voltage doubler
- Discuss voltage triplers
- Discuss voltage quadruplers

Voltage Doubler

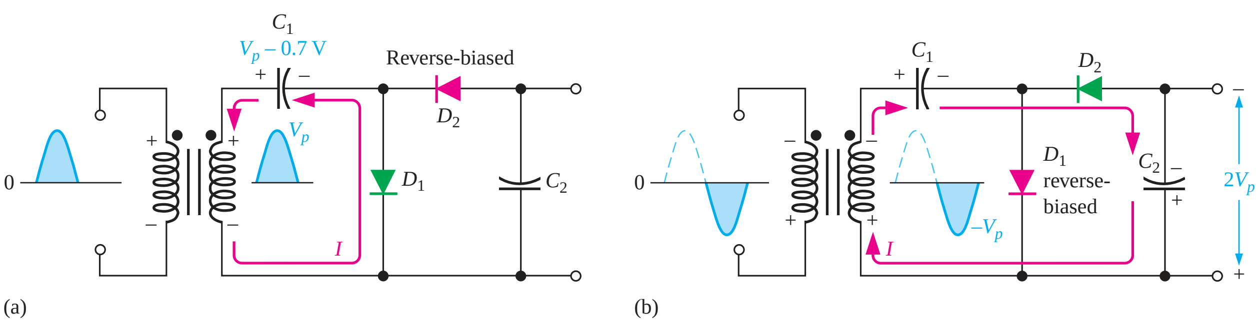
Half-Wave Voltage Doubler A voltage doubler is a **voltage multiplier** with a multiplication factor of two. A half-wave voltage doubler is shown in Figure 2–67. During the positive half-cycle of the secondary voltage, diode D_1 is forward-biased and D_2 is reverse-biased. Capacitor C_1 is charged to the peak of the secondary voltage (V_p) less the diode drop with the polarity shown in part (a). During the negative half-cycle, diode D_2 is forward-biased and D_1 is reverse-biased, as shown in part (b). Since C_1 can't discharge, the peak voltage on C_1 adds to the secondary voltage to charge C_2 to approximately $2V_p$. Applying Kirchhoff's law around the loop as shown in part (b), the voltage across C_2 is

$$V_{C1} - V_{C2} + V_p = 0$$

$$V_{C2} = V_p + V_{C1}$$

Neglecting the diode drop of D_2, $V_{C1} = V_p$. Therefore,

$$V_{C2} = V_p + V_p = 2V_p$$

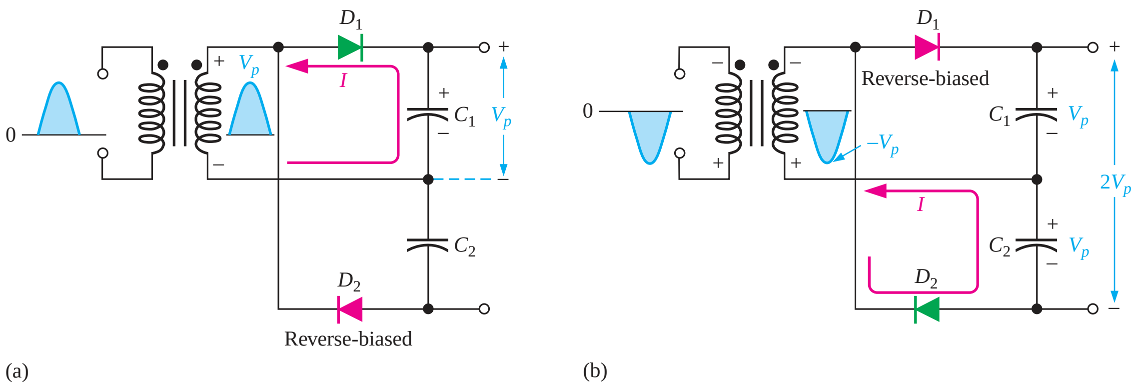


▲ FIGURE 2–67

Half-wave voltage doubler operation. V_p is the peak secondary voltage.

Under a no-load condition, C_2 remains charged to approximately $2V_p$. If a load resistance is connected across the output, C_2 discharges slightly through the load on the next positive half-cycle and is again recharged to $2V_p$ on the following negative half-cycle. The resulting output is a half-wave, capacitor-filtered voltage. The peak inverse voltage across each diode is $2V_p$. If the diode were reversed, the output voltage across C_2 would have the opposite polarity.

Full-Wave Voltage Doubler A full-wave doubler is shown in Figure 2–68. When the secondary voltage is positive, D_1 is forward-biased and C_1 charges to approximately V_p, as shown in part (a). During the negative half-cycle, D_2 is forward-biased and C_2 charges to approximately V_p, as shown in part (b). The output voltage, $2V_p$, is taken across the two capacitors in series.



▲ FIGURE 2–68

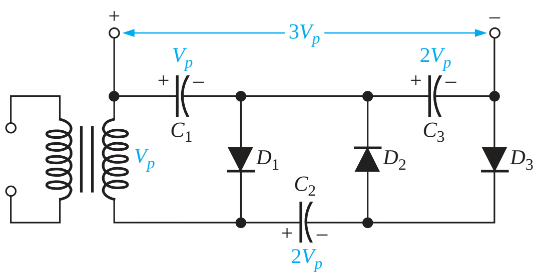
Full-wave voltage doubler operation.

Voltage Tripler

The addition of another diode-capacitor section to the half-wave voltage doubler creates a voltage tripler, as shown in Figure 2–69. The operation is as follows: On the positive half-cycle of the secondary voltage, C_1 charges to V_p through D_1. During the negative half-cycle, C_2 charges to $2V_p$ through D_2, as described for the doubler. During the next positive half-cycle, C_3 charges to $2V_p$ through D_3. The tripler output is taken across C_1 and C_3, as shown in the figure.

▶ FIGURE 2–69

Voltage tripler.

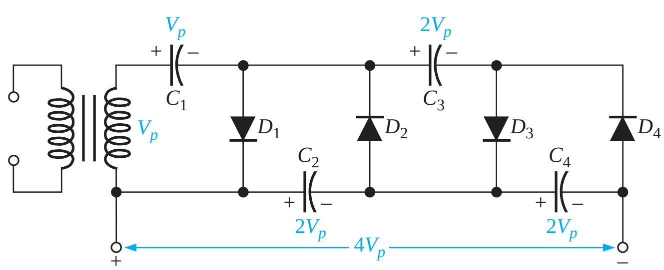


Voltage Quadrupler

The addition of still another diode-capacitor section, as shown in Figure 2–70, produces an output four times the peak secondary voltage. C_4 charges to $2V_p$ through D_4 on a negative half-cycle. The $4V_p$ output is taken across C_2 and C_4, as shown. In both the tripler and quadrupler circuits, the PIV of each diode is $2V_p$.

▶ FIGURE 2–70

Voltage quadrupler.



SECTION 2–8 CHECKUP

1. What must be the peak voltage rating of the transformer secondary for a voltage doubler that produces an output of 200 V?
2. The output voltage of a quadrupler is 620 V. What minimum PIV rating must each diode have?

2–9 THE DIODE DATASHEET

A manufacturer's datasheet gives detailed information on a device so that it can be used properly in a given application. A typical datasheet provides maximum ratings, electrical characteristics, mechanical data, and graphs of various parameters.

After completing this section, you should be able to

- **Interpret and use diode datasheets**
  ◆ Define several absolute maximum ratings ◆ Define diode thermal characteristics ◆ Define several electrical characteristics ◆ Interpret the forward current derating curve ◆ Interpret the forward characteristic curve ◆ Discuss nonrepetitive surge current ◆ Discuss the reverse characteristics

Figure 2–71 shows a typical rectifier diode datasheet. The presentation of information on datasheets may vary from one manufacturer to another, but they basically all convey the same information. The mechanical information, such as package dimensions, are not shown on this particular datasheet but are generally available from the manufacturer. Notice on this datasheet that there are three categories of data given in table form and four types of characteristics shown in graphical form.

Data Categories

Absolute Maximum Ratings The absolute maximum ratings indicate the maximum values of the several parameters under which the diode can be operated without damage or degradation. For greatest reliability and longer life, the diode should be operated well under these maximums. Generally, the maximum ratings are specified for an operating ambient temperature (T_A) of 25°C unless otherwise stated. Ambient temperature is the temperature of the air surrounding the device. The parameters given in Figure 2–71 are as follows:

V_{RRM} The peak reverse voltage that can be applied repetitively across the diode. Notice that it is 50 V for the 1N4001 and 1000 V for the 1N4007. This rating is the same as the PIV.

$I_{F(AV)}$ The maximum average value of a 60 Hz half-wave rectified forward current. This current parameter is 1.0 A for all of the diode types and is specified for an ambient temperature of 75°C.

I_{FSM} The maximum peak value of nonrepetitive single half-sine-wave forward surge current with a duration of 8.3 ms. This current parameter is 30 A for all of the diode types.

T_{stg} The allowable range of temperatures at which the device can be kept when not operating or connected to a circuit.

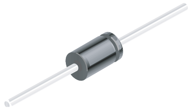
T_J The allowable range of temperatures for the *pn* junction when the diode is operated in a circuit.

FAIRCHILD SEMICONDUCTOR®

1N4001 - 1N4007

Features

- Low forward voltage drop.
- High surge current capability.



DO-41
COLOR BAND DENOTES CATHODE

General Purpose Rectifiers

Absolute Maximum Ratings* T_A = 25°C unless otherwise noted

Symbol	Parameter	Value							Units
		4001	4002	4003	4004	4005	4006	4007	
V_{RRM}	Peak Repetitive Reverse Voltage	50	100	200	400	600	800	1000	V
$I_{F(AV)}$	Average Rectified Forward Current, .375 " lead length @ T_A = 75°C	1.0							A
I_{FSM}	Non-repetitive Peak Forward Surge Current 8.3 ms Single Half-Sine-Wave	30							A
T_{stg}	Storage Temperature Range	-55 to +175							°C
T_J	Operating Junction Temperature	-55 to +175							°C

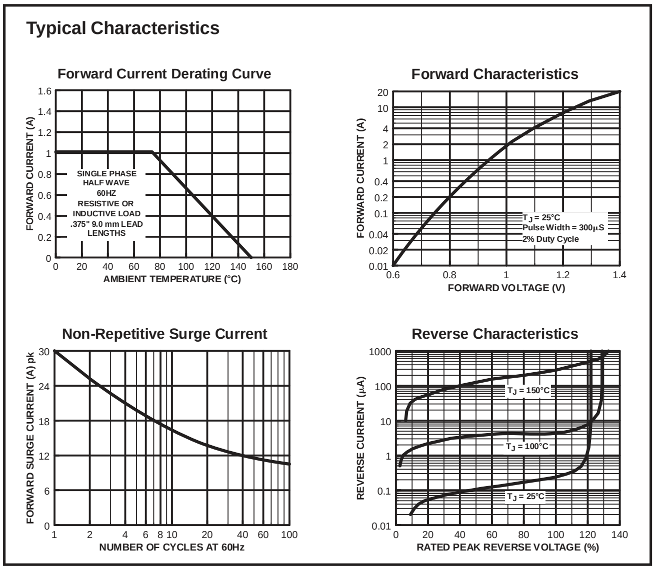
*These ratings are limiting values above which the serviceability of any semiconductor device may be impaired.

Thermal Characteristics

Symbol	Parameter	Value	Units
P_D	Power Dissipation	3.0	W
$R_{\theta JA}$	Thermal Resistance, Junction to Ambient	50	°C/W

Electrical Characteristics T_A = 25°C unless otherwise noted

Symbol	Parameter	Device							Units
		4001	4002	4003	4004	4005	4006	4007	
V_F	Forward Voltage @ 1.0 A	1.1							V
I_{rr}	Maximum Full Load Reverse Current, Full Cycle T_A = 75°C	30							µA
I_R	Reverse Current @ rated V_R T_A = 25°C T_A = 100°C	5.0 500							µA µA
C_T	Total Capacitance V_R = 4.0 V, f = 1.0 MHz	15							pF



▲ **FIGURE 2–71**

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Thermal Characteristics All devices have a limit on the amount of heat that they can tolerate without failing in some way.

P_D Average power dissipation is the amount of power that the diode can dissipate under any condition. A diode should never be operated at maximum power, except for brief periods, to assure reliability and longer life.

$R_{\theta JA}$ Thermal resistance from the diode junction to the surrounding air. This indicates the ability of the device material to resist the flow of heat and specifies the number of degrees difference between the junction and the surrounding air for each watt transferred from the junction to the air.

Electrical Characteristics The electrical characteristics are specified under certain conditions and are the same for each type of diode. These values are typical and can be more or less for a given diode. Some datasheets provide a minimum and a maximum value in addition to a typical value for a parameter.

V_F The forward voltage drop across the diode when there is 1 A of forward current. To determine the forward voltage for other values of forward current, you must examine the forward characteristics graph.

I_{rr} Maximum full load reverse current averaged over a full ac cycle at 75°C.

I_R The reverse current at the rated reverse voltage (V_{RRM}). Values are specified at two different ambient temperatures.

C_T This is the total diode capacitance including the junction capacitance in reverse bias at a frequency of 1 MHz. Most of the time this parameter is not important in low-frequency applications, such as power supply rectifiers.

Graphical Characteristics

The Forward Current Derating Curve This curve on the datasheet in Figure 2–71 shows maximum forward diode current $I_{F(AV)}$ in amps versus the ambient temperature. Up to about 75°C, the diode can handle a maximum of 1 A. Above 75°C, the diode cannot handle 1 A, so the maximum current must be derated as shown by the curve. For example, if a diode is operating in an ambient temperature of 120°C, it can handle only a maximum of 0.4 A, as shown in Figure 2–72.

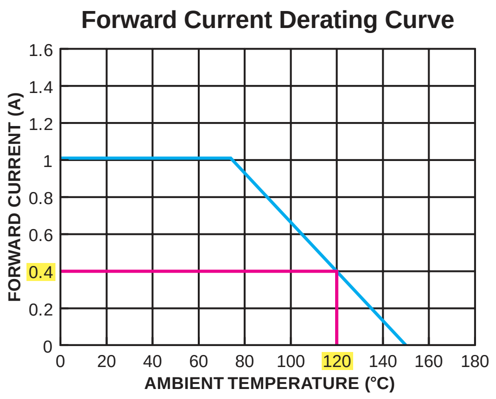


FIGURE 2–72

Forward Characteristics Curve Another graph from the datasheet shows instantaneous forward current as a function of instantaneous forward voltage. As indicated, data for this curve is derived by applying 300 μs pulses with a duty cycle of 2%. Notice that this graph is for $T_J = 25°C$. For example, a forward current of 1 A corresponds to a forward voltage of about 0.93 V, as shown in Figure 2–73.

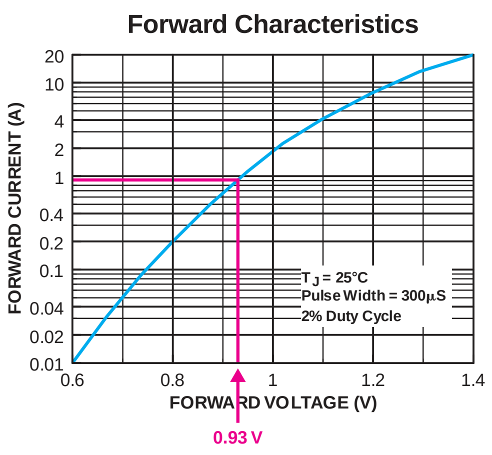
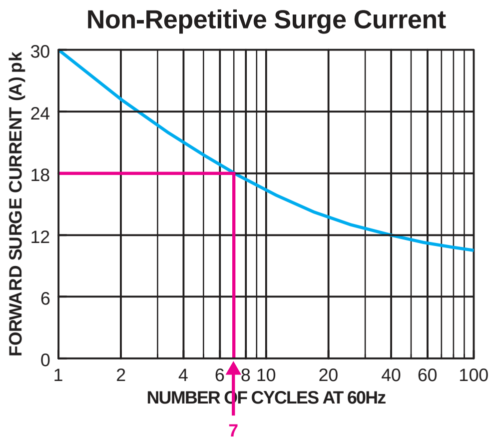


FIGURE 2–73

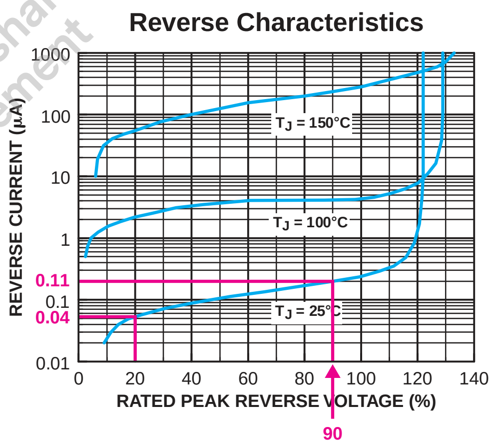
Nonrepetitive Surge Current This graph from the datasheet shows I_{FSM} as a function of the number of cycles at 60 Hz. For a one-time surge, the diode can withstand 30 A. However, if the surges are repeated at a frequency of 60 Hz, the maximum surge current decreases. For example, if the surge is repeated 7 times, the maximum current is 18 A, as shown in Figure 2–74.

▶ FIGURE 2–74



Reverse Characteristics This graph from the datasheet shows how the reverse current varies with the reverse voltage for three different junction temperatures. The horizontal axis is the percentage of maximum reverse voltage, V_{RRM}. For example, at 25°C, a 1N4001 has a reverse current of approximately 0.04 μA at 20% of its maximum V_{RRM} or 10 V. If the V_{RRM} is increased to 90%, the reverse current increases to approximately 0.11 μA, as shown in Figure 2–75.

▶ FIGURE 2–75



SECTION 2–9 CHECKUP

1. Determine the peak repetitive reverse voltage for each of the following diodes: 1N4002, 1N4003, 1N4004, 1N4005, 1N4006.
2. If the forward current is 800 mA and the forward voltage is 0.75 V in a 1N4005, is the power rating exceeded?
3. What is $I_{F(AV)}$ for a 1N4001 at an ambient temperature of 100°C?
4. What is I_{FSM} for a 1N4003 if the surge is repeated 40 times at 60 Hz?

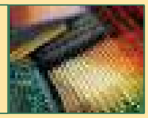
2–10 TROUBLESHOOTING

This section provides a general overview and application of an approach to troubleshooting. Specific troubleshooting examples of the power supply and diode circuits are covered.

After completing this section, you should be able to

- **Troubleshoot diodes and power supply circuits**
- Test a diode with a DMM
  - Use the diode test position
  - Determine if the diode is good or bad
  - Use the Ohms function to check a diode
- Troubleshoot a dc power supply by analysis, planning, and measurement
  - Use the half-splitting method
- Perform fault analysis
  - Isolate fault to a single component

Chapter 18: Basic Programming Concepts for Automated Testing
Selected sections from Chapter 18 may be introduced as part of this troubleshooting coverage or, optionally, the entire Chapter 18 may be covered later or not at all.



Testing a Diode

A multimeter can be used as a fast and simple way to check a diode out of the circuit. A good diode will show an extremely high resistance (ideally an open) with reverse bias and a very low resistance with forward bias. A defective open diode will show an extremely high resistance (or open) for both forward and reverse bias. A defective shorted or resistive diode will show zero or a low resistance for both forward and reverse bias. An open diode is the most common type of failure.

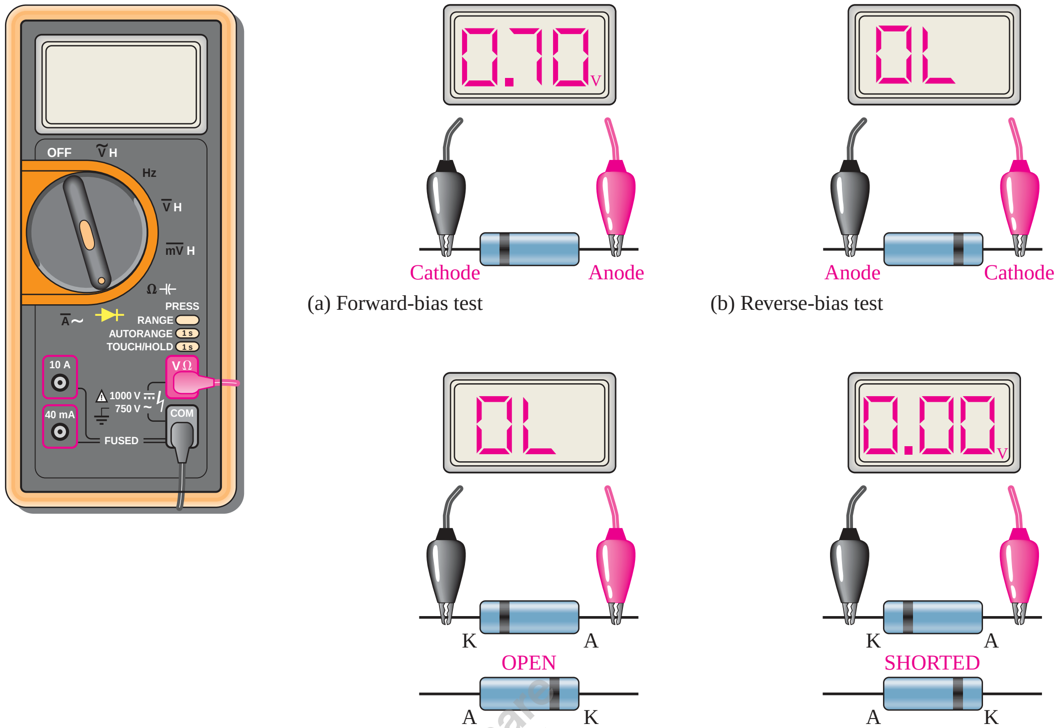
The DMM Diode Test Position Many digital multimeters (DMMs) have a diode test function that provides a convenient way to test a diode. A typical DMM, as shown in Figure 2–76, has a small diode symbol to mark the position of the function switch. When set to *diode test*, the meter provides an internal voltage sufficient to forward-bias and reverse-bias a diode. This internal voltage may vary among different makes of DMM, but 2.5 V to 3.5 V is a typical range of values. The meter provides a voltage reading or other indication to show the condition of the diode under test.

When the Diode Is Working In Figure 2–76(a), the red (positive) lead of the meter is connected to the anode and the black (negative) lead is connected to the cathode to forward-bias the diode. If the diode is good, you will get a reading of between approximately 0.5 V and 0.9 V, with 0.7 V being typical for forward bias.

In Figure 2–76(b), the diode is turned around for reverse bias as shown. If the diode is working properly, you will typically get a reading of "OL". Some DMMs may display the internal voltage for a reverse-bias condition.

When the Diode Is Defective When a diode has failed open, you get an out-of-range "OL" indication for both the forward-bias and the reverse-bias conditions, as illustrated in Figure 2–76(c). If a diode is shorted, the meter reads 0 V in both forward- and reverse-bias tests, as indicated in part (d).

Checking a Diode with the OHMs Function DMMs that do not have a diode test position can be used to check a diode by setting the function switch on an OHMs range. For a forward-bias check of a good diode, you will get a resistance reading that can vary depending on the meter's internal battery. Many meters do not have sufficient voltage on the OHMs setting to fully forward-bias a diode and you may get a reading of from several hundred to several thousand ohms. For the reverse-bias check of a good diode, you will get an



(a) Forward-bias test

(b) Reverse-bias test

(c) Forward- and reverse-bias tests for an open diode give the same indication.

(d) Forward- and reverse-bias tests for a shorted diode give the same 0 V reading.

▲ **FIGURE 2–76**

Testing a diode out-of-circuit with a DMM.

out-of-range indication such as "OL" on most DMMs because the reverse resistance is too high for the meter to measure.

Even though you may not get accurate forward- and reverse-resistance readings on a DMM, the relative readings indicate that a diode is functioning properly, and that is usually all you need to know. The out-of-range indication shows that the reverse resistance is extremely high, as you expect. The reading of a few hundred to a few thousand ohms for forward bias is relatively small compared to the reverse resistance, indicating that the diode is working properly. The actual resistance of a forward-biased diode is typically much less than 100 Ω.

SAFETY NOTE

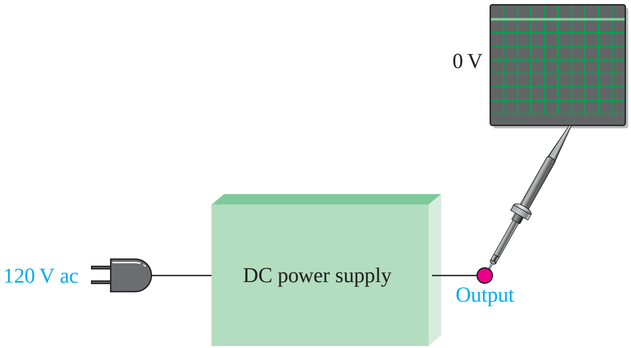
When working with low-voltage power supplies, be careful not to come in contact with the 120 V ac line. Severe shock or worse could result. To verify input voltage to a rectifier, it is always better to check at the transformer secondary instead of trying to measure the line voltage directly. If it becomes necessary to measure the line voltage, use a multimeter and be careful.

Troubleshooting a Power Supply

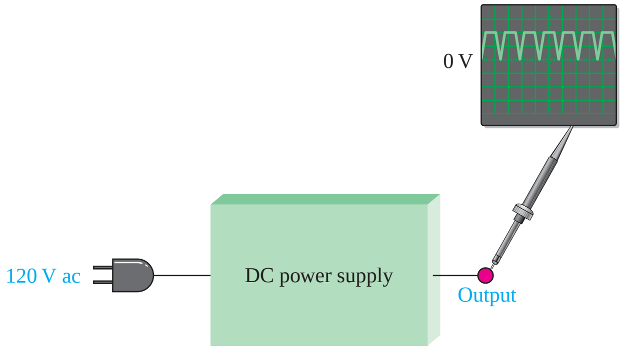
Troubleshooting is the application of logical thinking combined with a thorough knowledge of circuit or system operation to identify and correct a malfunction. A systematic approach to troubleshooting consists of three steps: *analysis, planning*, and *measuring.*

A defective circuit or system is one with a known good input but with no output or an incorrect output. For example, in Figure 2–77(a), a properly functioning dc power supply is represented by a single block with a known input voltage and a correct output voltage. A defective dc power supply is represented in part (b) as a block with an input voltage and an incorrect output voltage.

Analysis The first step in troubleshooting a defective circuit or system is to analyze the problem, which includes identifying the symptom and eliminating as many causes as possible. In the case of the power supply example illustrated in Figure 2–77(b), the symptom is that the output voltage is not a constant regulated dc voltage. This symptom does not tell you much about what the specific cause may be. In other situations, however, a particular symptom may point to a given area where a fault is most likely.



(a) The correct dc output voltage is measured with oscilloscope.



(b) An incorrect voltage is measured at the output with oscilloscope.

▲ FIGURE 2–77

Block representations of functioning and nonfunctioning power supplies.

The first thing you should do in analyzing the problem is to try to eliminate any obvious causes. In general, you should start by making sure the power cord is plugged into an active outlet and that the fuse is not blown. In the case of a battery-powered system, make sure the battery is good. Something as simple as this is sometimes the cause of a problem. However, in this case, there must be power because there is an output voltage.

Beyond the power check, use your senses to detect obvious defects, such as a burned resistor, broken wire, loose connection, or an open fuse. Since some failures are temperature dependent, you can sometimes find an overheated component by touch. However, be very cautious in a live circuit to avoid possible burn or shock. For intermittent failures, the circuit may work properly for awhile and then fail due to heat buildup. As a rule, you should always do a sensory check as part of the analysis phase before proceeding.

Planning In this phase, you must consider how you will attack the problem. There are three possible approaches to troubleshooting most circuits or systems.

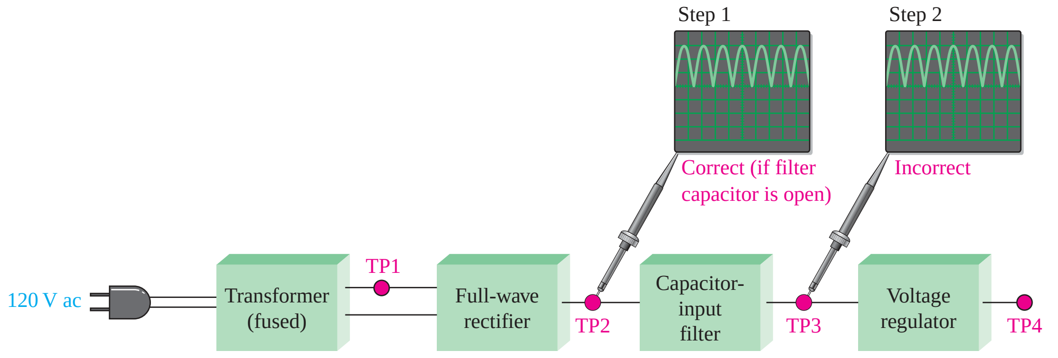
1. Start at the input (the transformer secondary in the case of a dc power supply) where there is a known input voltage and work toward the output until you get an incorrect measurement. When you find no voltage or an incorrect voltage, you have narrowed the problem to the part of the circuit between the last test point where the voltage was good and the present test point. In all troubleshooting approaches, you must know what the voltage is supposed to be at each point in order to recognize an incorrect measurement when you see it.

2. Start at the output of a circuit and work toward the input. Check for voltage at each test point until you get a correct measurement. At this point, you have isolated the problem to the part of the circuit between the last test point and the current test point where the voltage is correct.

3. Use the half-splitting method and start in the middle of the circuit. If this measurement shows a correct voltage, you know that the circuit is working properly from the input to that test point. This means that the fault is between the current test point and the output point, so begin tracing the voltage from that point toward the output. If the measurement in the middle of the circuit shows no voltage or an incorrect voltage, you know that the fault is between the input and that test point. Therefore, begin tracing the voltage from the test point toward the input.

For illustration, let's say that you decide to apply the half-splitting method using an oscilloscope.

Measurement The half-splitting method is illustrated in Figure 2–78 with the measurements indicating a particular fault (open filter capacitor in this case). At test point 2 (TP2) you observe a full-wave rectified voltage that indicates that the transformer and rectifier

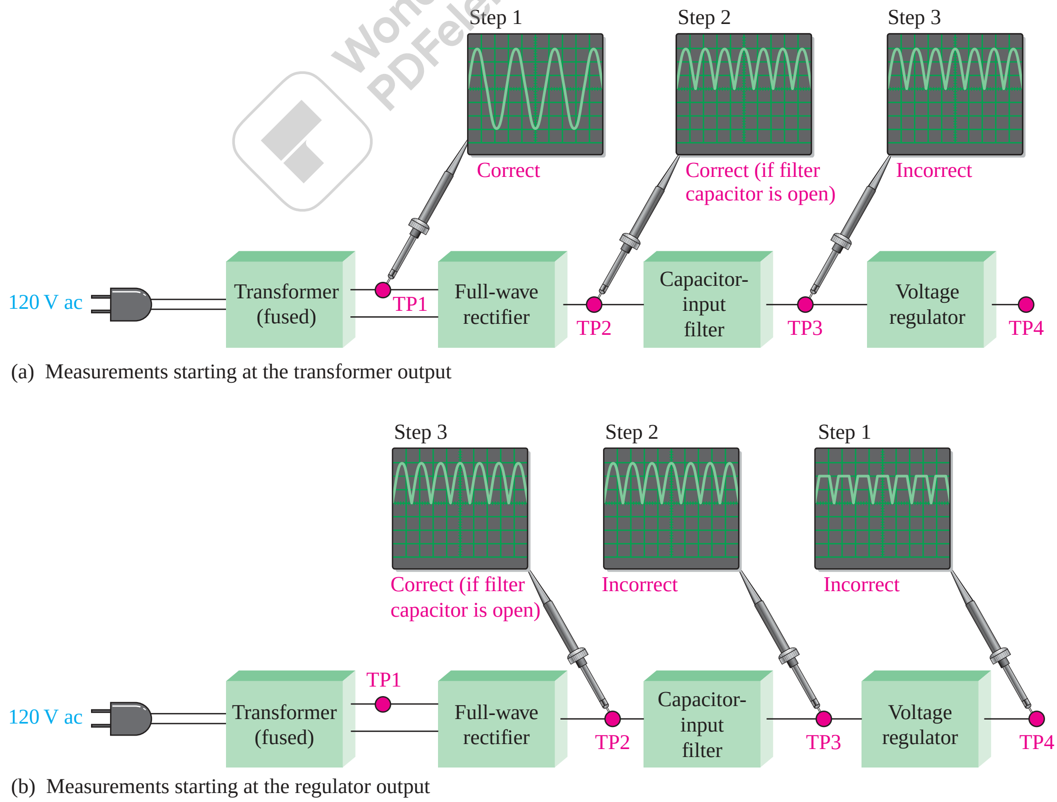


▲ **FIGURE 2–78**

Example of the half-splitting approach. An open filter capacitor is indicated.

are working properly. This measurement also indicates that the filter capacitor is open, which is verified by the full-wave voltage at TP3. If the filter were working properly, you would measure a dc voltage at both TP2 and TP3. If the filter capacitor were shorted, you would observe no voltage at all of the test points because the fuse would most likely be blown. A short anywhere in the system is very difficult to isolate because, if the system is properly fused, the fuse will blow immediately when a short to ground develops.

For the case illustrated in Figure 2–78, the half-splitting method took two measurements to isolate the fault to the open filter capacitor. If you had started from the transformer output, it would have taken three measurements; and if you had started at the final output, it would have also taken three measurements, as illustrated in Figure 2–79.



▲ **FIGURE 2–79**

In this particular case, the two other approaches require more oscilloscope measurements than the half-splitting approach in Figure 2–78.

Fault Analysis

In some cases, after isolating a fault to a particular circuit, it may be necessary to isolate the problem to a single component in the circuit. In this event, you have to apply logical thinking and your knowledge of the symptoms caused by certain component failures. Some typical component failures and the symptoms they produce are now discussed.

Effect of an Open Diode in a Half-Wave Rectifier A half-wave filtered rectifier with an open diode is shown in Figure 2–80. The resulting symptom is zero output voltage as indicated. This is obvious because the open diode breaks the current path from the transformer secondary winding to the filter and load resistor and there is no load current.

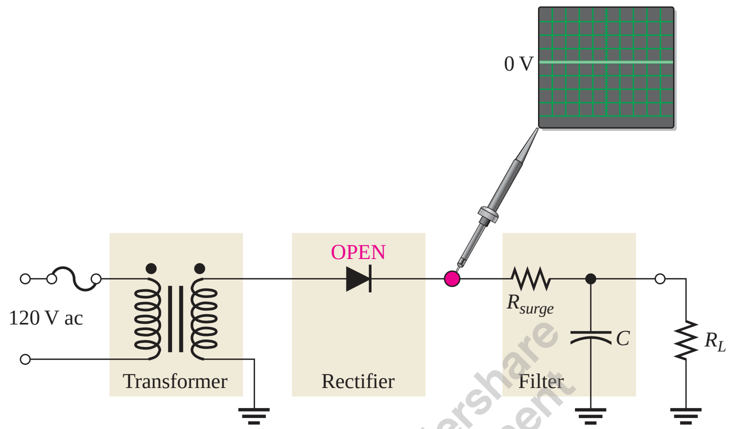


FIGURE 2–80

The effect of an open diode in a half-wave rectifier is an output of 0 V.

Other faults that will cause the same symptom in this circuit are an open transformer winding, an open fuse, or no input voltage.

Effect of an Open Diode in a Full-Wave Rectifier A full-wave center-tapped filtered rectifier is shown in Figure 2–81. If either of the two diodes is open, the output voltage will have twice the normal ripple voltage at 60 Hz rather than at 120 Hz, as indicated.

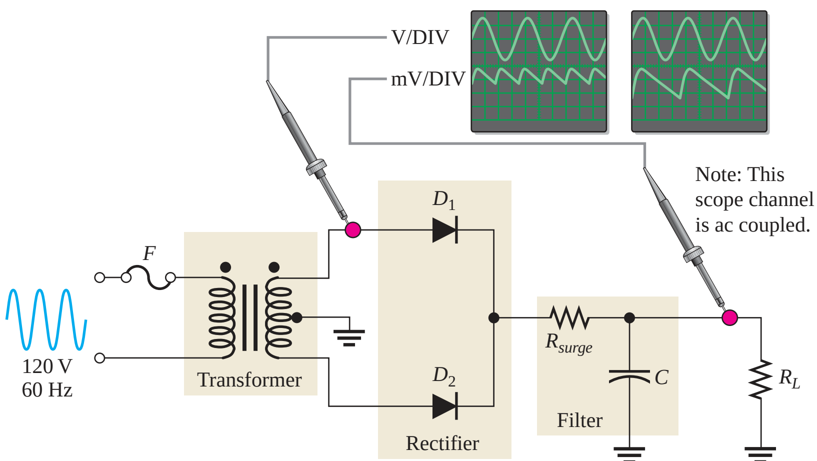


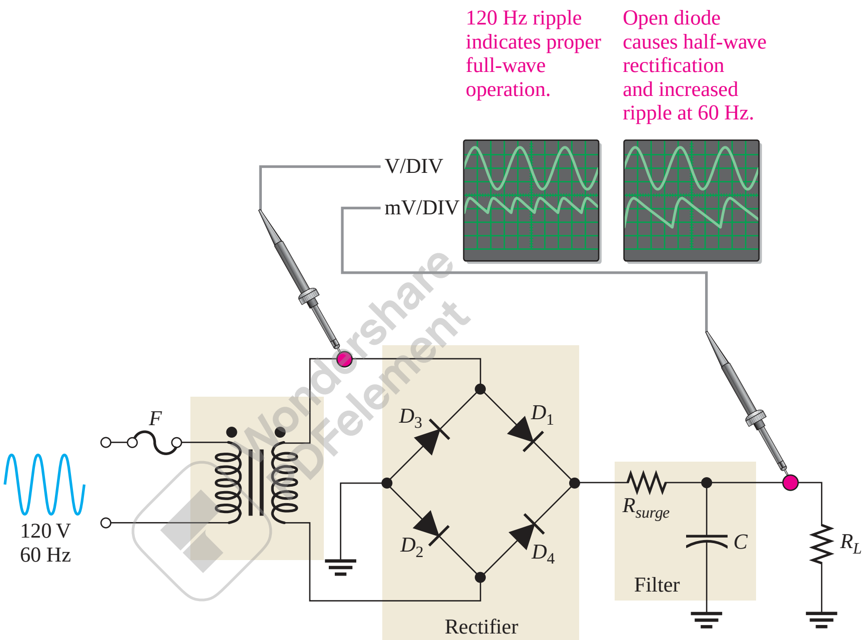
FIGURE 2–81

The effect of an open diode in a center-tapped rectifier is half-wave rectification and twice the ripple voltage at 60 Hz.

Another fault that will cause the same symptom is an open in the transformer secondary winding.

The reason for the increased ripple at 60 Hz rather than at 120 Hz is as follows. If one of the diodes in Figure 2–81 is open, there is current through R_L only during one half-cycle of the input voltage. During the other half-cycle of the input, the open path caused by the open diode prevents current through R_L. The result is half-wave rectification, as shown in Figure 2–81, which produces the larger ripple voltage with a frequency of 60 Hz.

An open diode in a full-wave bridge rectifier will produce the same symptom as in the center-tapped circuit, as shown in Figure 2–82. The open diode prevents current through R_L during half of the input voltage cycle. The result is half-wave rectification, which produces double the ripple voltage at 60 Hz.



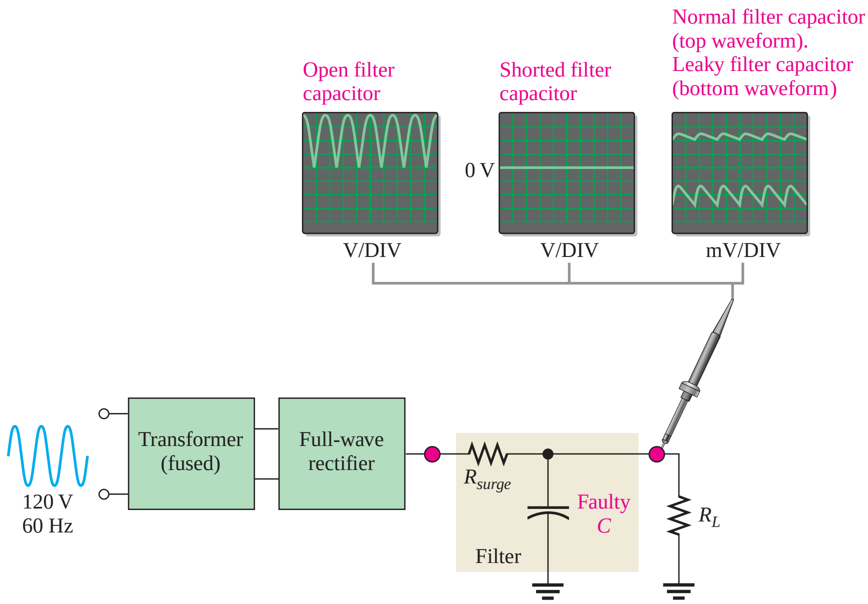
▲ **FIGURE 2–82**

Effect of an open diode in a bridge rectifier.

Effects of a Faulty Filter Capacitor Three types of defects of a filter capacitor are illustrated in Figure 2–83.

- *Open* If the filter capacitor for a full-wave rectifier opens, the output is a full-wave rectified voltage.
- *Shorted* If the filter capacitor shorts, the output is 0 V. A shorted capacitor should cause the fuse to blow open. If not properly fused, a shorted capacitor may cause some or all of the diodes in the rectifier to burn open due to excessive current. In any event, the output is 0 V.
- *Leaky* A leaky filter capacitor is equivalent to a capacitor with a parallel leakage resistance. The effect of the leakage resistance is to reduce the time constant and allow the capacitor to discharge more rapidly than normal. This results in an increase in the ripple voltage on the output. This fault is rare.

Effects of a Faulty Transformer An open primary or secondary winding of a power supply transformer results in an output of 0 V, as mentioned before.

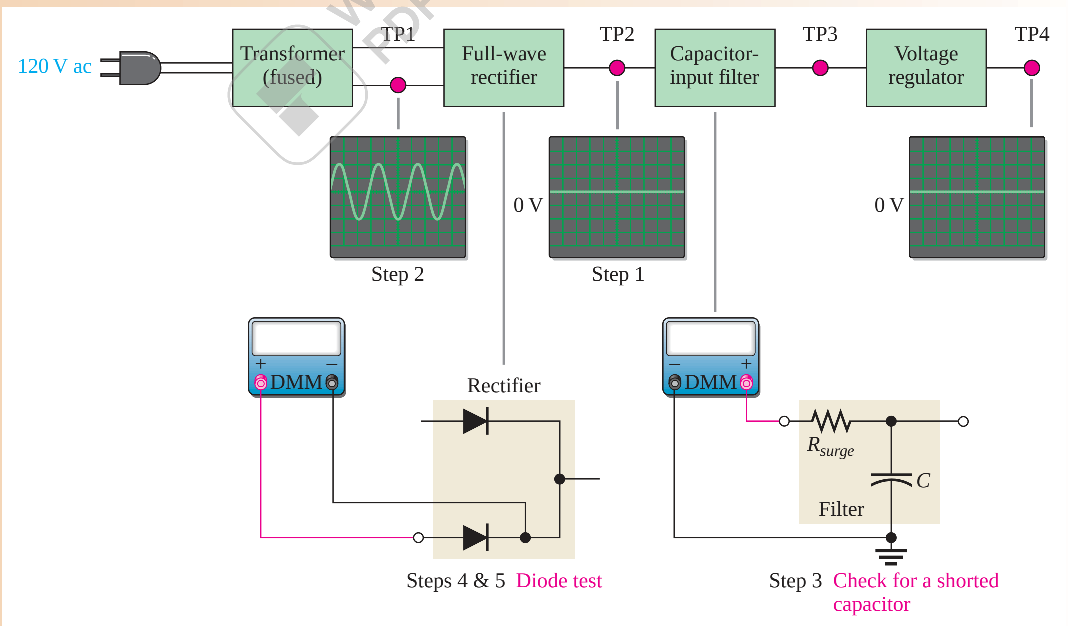


◀ **FIGURE 2–83**

Effects of a faulty filter capacitor.

EXAMPLE 2–14

You are troubleshooting the power supply shown in the block diagram of Figure 2–84. You have found in the analysis phase that there is no output voltage from the regulator, as indicated. Also, you have found that the unit is plugged into the outlet and have verified the input to the transformer with a DMM. You decide to use the half-splitting method using the scope. What is the problem?



▲ **FIGURE 2–84**

Solution The step-by-step measurement procedure is illustrated in the figure and described as follows.

Step 1: There is no voltage at test point 2 (TP2). This indicates that the fault is between the input to the transformer and the output of the rectifier. Most likely, the problem is in the transformer or in the rectifier, but there may be a short from the filter input to ground.

Step 2: The voltage at test point 1 (TP1) is correct, indicating that the transformer is working. So, the problem must be in the rectifier or a shorted filter input.

Step 3: With the power turned off, use a DMM to check for a short from the filter input to ground. Assume that the DMM indicates no short. The fault is now isolated to the rectifier.

Step 4: Apply fault analysis to the rectifier circuit. Determine the component failure in the rectifier that will produce a 0 V input. If only one of the diodes in the rectifier is open, there should be a half-wave rectified output voltage, so this is not the problem. In order to have a 0 V output, there must be an open in the rectifier circuit.

Step 5: With the power off, use the DMM in the diode test mode to check each diode. Replace the defective diodes, turn the power on, and check for proper operation. Assume this corrects the problem.

Related Problem Suppose you had found a short in Step 3, what would have been the logical next step?

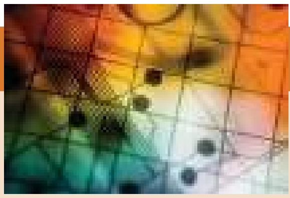
Multisim Troubleshooting Exercises

These file circuits are in the Troubleshooting Exercises folder on the companion website. Open each file and determine if the circuit is working properly. If it is not working properly, determine the fault.

1. Multisim file TSE02-01
2. Multisim file TSE02-02
3. Multisim file TSE02-03
4. Multisim file TSE02-04

SECTION 2–10 CHECKUP

1. A properly functioning diode will produce a reading in what range when forward-biased?
2. What reading might a DMM produce when a diode is reverse-biased?
3. What effect does an open diode have on the output voltage of a half-wave rectifier?
4. What effect does an open diode have on the output voltage of a full-wave rectifier?
5. If one of the diodes in a bridge rectifier shorts, what are some possible consequences?
6. What happens to the output voltage of a rectifier if the filter capacitor becomes very leaky?
7. The primary winding of the transformer in a power supply opens. What will you observe on the rectifier output?
8. The dc output voltage of a filtered rectifier is less than it should be. What may be the problem?



Application Activity: *DC Power Supply*

Assume that you are working for a company that designs, tests, manufactures, and markets various electronic instruments including dc power supplies. Your first assignment is to develop and test a basic unregulated power supply using the knowledge that you have acquired so far. Later modifications will include the addition of a regulator. The power supply must meet or exceed the following specifications:

- Input voltage: 120 V rms @60 Hz
- Output voltage: 16 V dc ±10%
- Ripple factor (max): 3.00%
- Load current (max): 250 mA

Design of the Power Supply

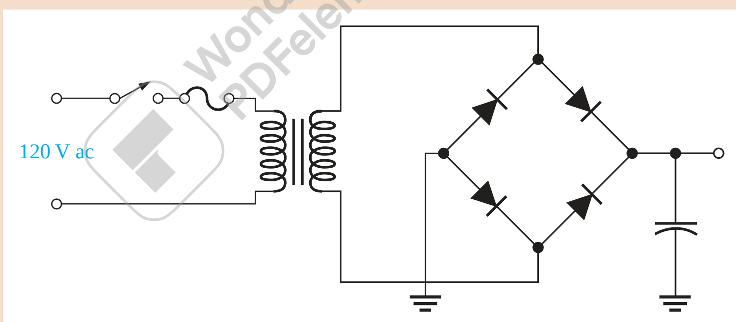
The Rectifier Circuit A full-wave rectifier has less ripple for a given filter capacitor than a half-wave rectifier. A full-wave bridge rectifier is probably the best choice because it provides the most output voltage for a given input voltage and the PIV is less than for a center-tapped rectifier. Also, the full-wave bridge does not require a center-tapped transformer.

1. Compare Equations 2–7 and 2–9 for output voltages.
2. Compare Equations 2–8 and 2–10 for PIV.

The full-wave bridge rectifier circuit is shown in Figure 2–85.

▶ **FIGURE 2–85**

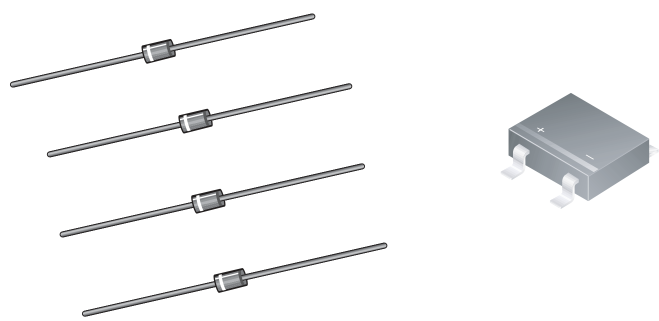
Power supply with full-wave bridge rectifier and capacitor filter.



The Rectifier Diodes There are two approaches for implementing the full-wave bridge: Four individual diodes, as shown in Figure 2–86(a) or a single IC package containing four diodes connected as a bridge rectifier, as shown in part (b).

▶ **FIGURE 2–86**

Rectifier components.



(a) Separate rectifier diodes (b) Full-wave bridge rectifier

Because the rectifier in the single IC package exceeds the specifications and requires less wiring on a board, takes up less space, and requires stocking and handling of only one component versus four, it is the best choice. Another factor to consider is the cost. Requirements for the diodes in the bridge are

- Forward current rating must be equal or greater than 250 mA (maximum load current).
- PIV must be greater than the minimum calculated value of 16.7 V ($\text{PIV} = V_{p(out)} + 0.7\text{ V}$).

By reviewing manufacturer's datasheets on-line, a specific device can be chosen. Figure 2–87 shows a partial datasheet for the rectifier to be used for this power supply. Notice that it exceeds the specified requirements. Four possible websites for rectifiers and diodes are *fairchildsemiconductor.com; onsemi.com*; *semiconductor.phillips.com*; and *rectron.com*.

▶ **FIGURE 2–87**

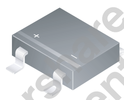
Rectifier datasheet. You can view the entire datasheet at www.fairchildsemiconductor.com. Copyright Fairchild Semiconductor Corporation. Used by permission.

FAIRCHILD SEMICONDUCTOR®

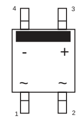
MB1S - MB8S

Features

- Low leakage
- Surge overload rating: 35 amperes peak.
- Ideal for printed circuit board.
- UL certified, UL #E111753.



SOIC-4
Polarity symbols molded or marking on body



Bridge Rectifiers

Absolute Maximum Ratings* $T_A = 25°C$ unless otherwise noted

Symbol	Parameter	Value					Units
		1S	2S	4S	6S	8S	
V_{RRM}	Maximum Repetitive Reverse Voltage	100	200	400	600	800	V
V_{RMS}	Maximum RMS Bridge Input Voltage	70	140	280	420	560	V
V_R	DC Reverse Voltage (Rated V_R)	100	200	400	600	800	V
$I_{F(AV)}$	Average Rectified Forward Current, @ $T_A = 50°C$	0.5					A
I_{FSM}	Non-repetitive Peak Forward Surge Current 8.3 ms Single Half-Sine-Wave	35					A
T_{stg}	Storage Temperature Range	-55 to +150					°C
T_J	Operating Junction Temperature	-55 to +150					°C

*These ratings are limiting values above which the serviceability of any semiconductor device may be impaired.

Thermal Characteristics

Symbol	Parameter	Value	Units
P_D	Power Dissipation	1.4	W
$R_{\theta JA}$	Thermal Resistance, Junction to Ambient,* per leg	85	°C/W
$R_{\theta JL}$	Thermal Resistance, Junction to Lead,* per leg	20	°C/W

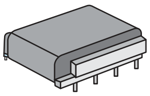
*Device mounted on PCB with 0.5-0.5" (13x13 mm) lead length.

Electrical Characteristics $T_A = 25°C$ unless otherwise noted

Symbol	Parameter	Device	Units
V_F	Forward Voltage, per bridge @ 0.5 A	1.0	V
I_R	Reverse Current, per leg @ rated V_R $T_A = 25°C$ / $T_A = 125°C$	5.0 / 0.5	A / mA
	I^2t rating for fusing $t < 8.3$ ms	5.0	A^2s
C_T	Total Capacitance, per leg $V_R = 4.0$ V, f = 1.0 MHz	13	pF

The Transformer The transformer must convert the 120 V line voltage to an ac voltage that will result in a rectified voltage that will produce 16 V±10% when filtered. A typical power transformer for mounting on a printed circuit board and a portion of a datasheet for the series are shown in Figure 2–88. Notice that transformer power is measured in VA (volt-amps), not watts.

3. Use Equation 2–9 to calculate the required transformer secondary rms voltage.
4. From the partial datasheet in Figure 2–88, select an appropriate transformer based on its secondary voltage (series) and a VA specification that meets the requirement.
5. Determine the required fuse rating.



	Secondary		Dimensions					
VA	Series	Parallel	H	W	L	A	B	Wt. Oz.
2.5	10.0V CT @ 0.25A	5.0V @ 0.5A	0.650	1.562	1.875	1.600	0.375	5
2.5	12.6V CT @ 0.2A	6.3V @ 0.4A	0.650	1.562	1.875	1.600	0.375	5
2.5	16.0V CT @ 0.15A	8.0V @ 0.3A	0.650	1.562	1.875	1.600	0.375	5
2.5	20.0V CT @ 0.125A	10.0V @ 0.25A	0.650	1.562	1.875	1.600	0.375	5
2.5	24.0V CT @ 0.1A	12.0V @ 0.2A	0.650	1.562	1.875	1.600	0.375	5
2.5	30.0V CT @ 0.08A	15.0V @ 0.16A	0.650	1.562	1.875	1.600	0.375	5
2.5	34.0V CT @ 0.076A	17.0V @ 0.15A	0.650	1.562	1.875	1.600	0.375	5
2.5	40.0V CT @ 0.06A	20.0V @ 0.12A	0.650	1.562	1.875	1.600	0.375	5
2.5	56.0V CT @ 0.045A	28.0V @ 0.09A	0.650	1.562	1.875	1.600	0.375	5
2.5	88.0V CT @ 0.028A	44.0V @ 0.056A	0.650	1.562	1.875	1.600	0.375	5
2.5	120.0V CT @ 0.02A	60.0V @ 0.04A	0.650	1.562	1.875	1.600	0.375	5
2.5	230.0V CT @ 0.01A	115.0V @ 0.02A	0.650	1.562	1.875	1.600	0.375	5
6.0	10.0V CT @ 0.6A	5.0V @ 1.2A	0.875	1.562	1.875	1.600	0.375	7
6.0	12.0V CT @ 0.475A	6.3V @ 0.95A	0.875	1.562	1.875	1.600	0.375	7
6.0	16.0V CT @ 0.375A	8.0V @ 0.75A	0.875	1.562	1.875	1.600	0.375	7
6.0	20.0V CT @ 0.3A	10.0V @ 0.6A	0.875	1.562	1.875	1.600	0.375	7
6.0	24.0V CT @ 0.25A	12.0V @ 0.5A	0.875	1.562	1.875	1.600	0.375	7

▲ **FIGURE 2–88**

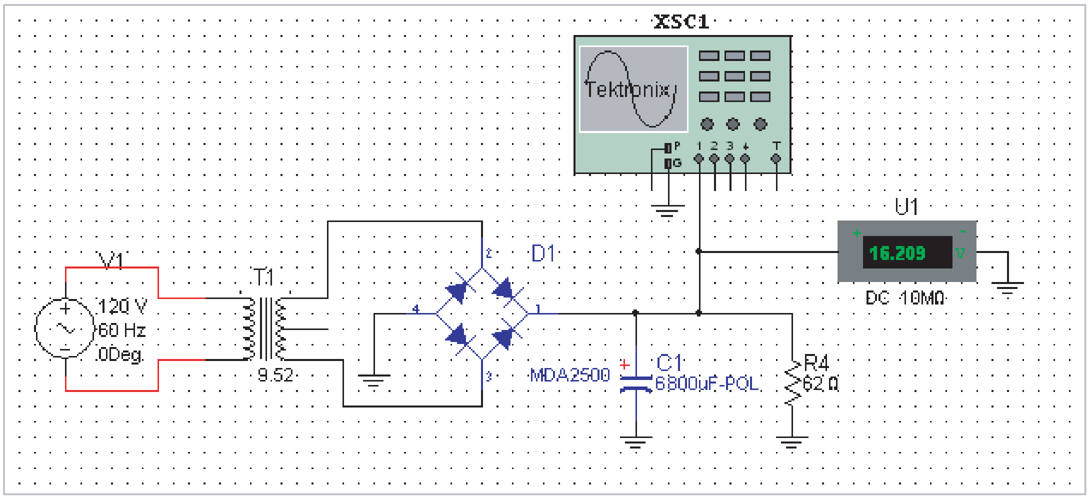
Typical pc-mounted power transformer and data. Volts are rms.

The Filter Capacitor The capacitance of the filter capacitor must be sufficiently large to provide the specified ripple.

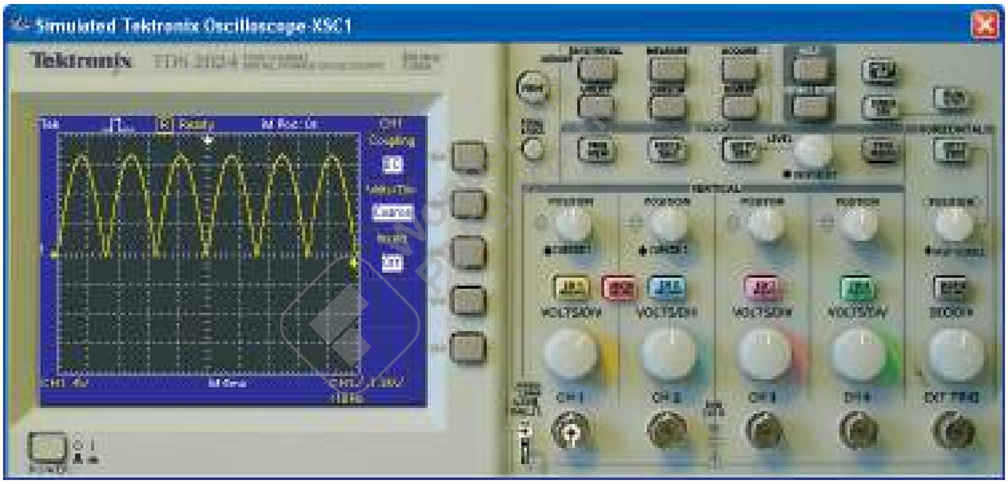
6. Use Equation 2–11 to calculate the peak-to-peak ripple voltage, assuming $V_{DC} = 16$ V.
7. Use Equation 2–12 to calculate the minimum capacitance value. Use $R_L = 64\ \Omega$, calculated on page 89.

Simulation

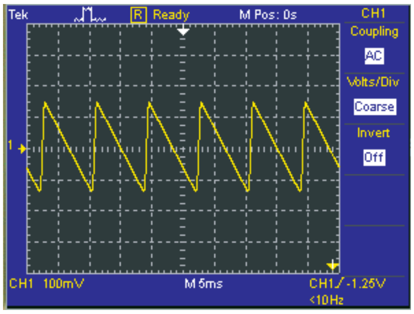
In the development of a new circuit, it is sometimes helpful to simulate the circuit using a software program before actually building it and committing it to hardware. We will use Multisim to simulate this power supply circuit. Figure 2–89 shows the simulated power



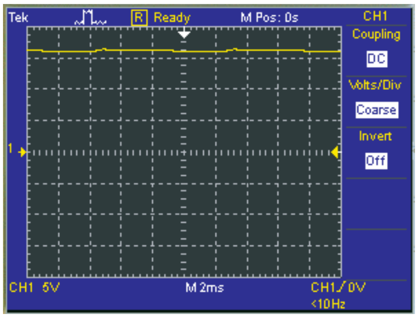
(a) Multisim circuit screen



(b) Output voltage without the filter capacitor



(c) Ripple voltage is less than 300 mV pp



(d) DC output voltage with filter capacitor (near top of screen)

▲ **FIGURE 2–89**

Power supply simulation.

supply circuit with a load connected and scope displays of the output voltage with and without the filter capacitor connected. The filter capacitor value of 6800 μF is the next highest standard value closest to the minimum calculated value required. A load resistor value was chosen to draw a current equal to or greater than the specified maximum load current.

$$R_L = \frac{16\text{ V}}{250\text{ mA}} = 64\ \Omega$$

The closest standard value is 62 Ω, which draws 258 mA at 16 V and which meets and exceeds the load current specification.

8. Determine the power rating for the load resistor.

To produce a dc output of 16 V, a peak secondary voltage of 16 V + 1.4 V = 17.4 V is required. The rms secondary voltage must be

$$V_{rms(sec)} = 0.707V_{p(sec)} = 0.707(16\text{ V} + 1.4\text{ V}) = 12.3\text{ V}$$

SAFETY NOTE

Be very careful to not touch the line voltage connections to the transformer primary. In normal practice, the board is housed in a protective box to prevent the possibility of contact with the 120 V ac line.

A standard transformer rms output voltage is 12.6 V. The transformer specification required by Multisim is

$$120\text{ V}:12.6\text{ V} = 9.52:1$$

The dc voltmeter in Figure 2–89(a) indicates an output voltage of 16.209 V, which is well within the 16 V±10% requirement. In part (c), the scope is AC coupled and set at 100 mV/division. You can see that the peak-to-peak ripple voltage is less than 300 mV, which is less than 480 mV, corresponding to the specified maximum ripple factor of 3%.

Build and simulate the circuit using your Multisim software. Observe the operation with the virtual oscilloscope and voltmeter.

Prototyping and Testing

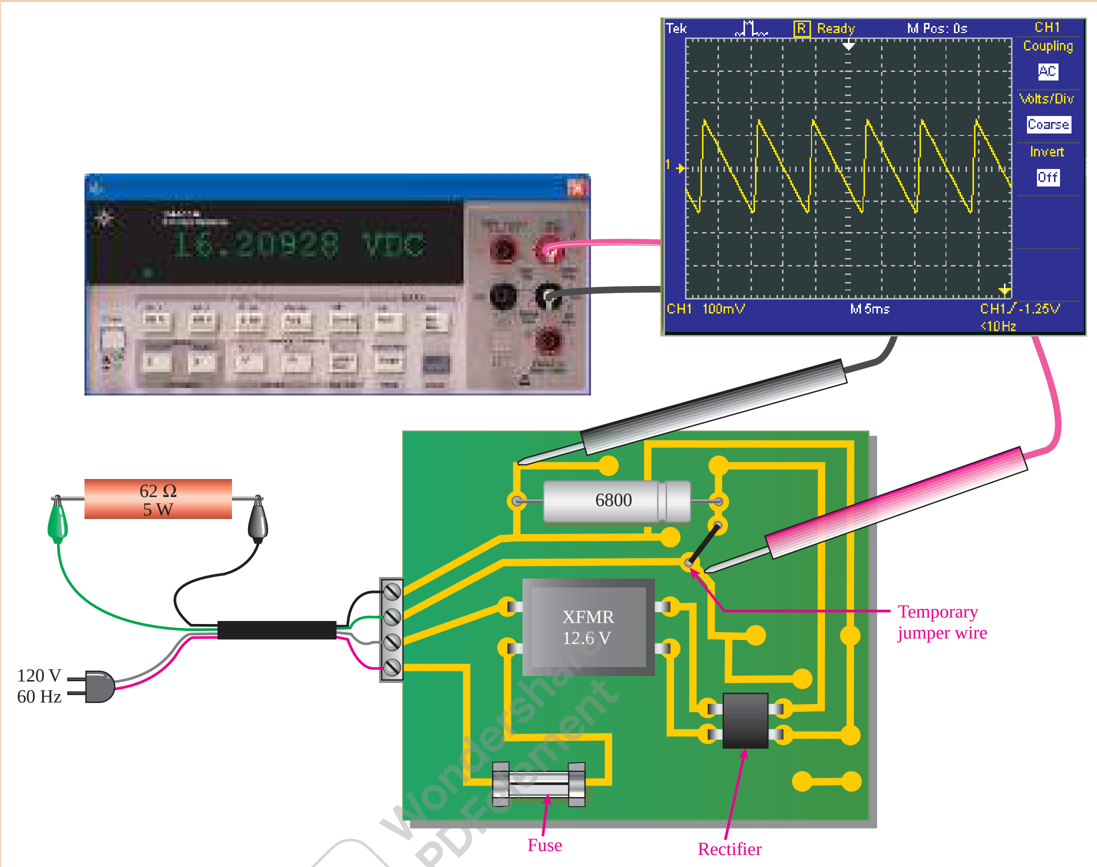
Now that all the components have been selected, the prototype circuit is constructed and tested. After the circuit is successfully tested, it is ready to be finalized on a printed circuit board.

Lab Experiment

To build and test a similar circuit, go to Experiment 2 in your lab manual (*Laboratory Exercises for Electronic Devices* by David Buchla and Steven Wetterling).

The Printed Circuit Board

The circuit board is shown in Figure 2–90. There are additional traces and connection points on the board for expansion to a regulated power supply, which will be done in Chapter 3. The circuit board is connected to the ac voltage and to a power load resistor via a cable. The power switch shown in the original schematic will be on the PC board housing and is not shown for the test setup. A DMM measurement of the output voltage indicates a correct value. Oscilloscope measurement of the ripple shows that it is within specifications.

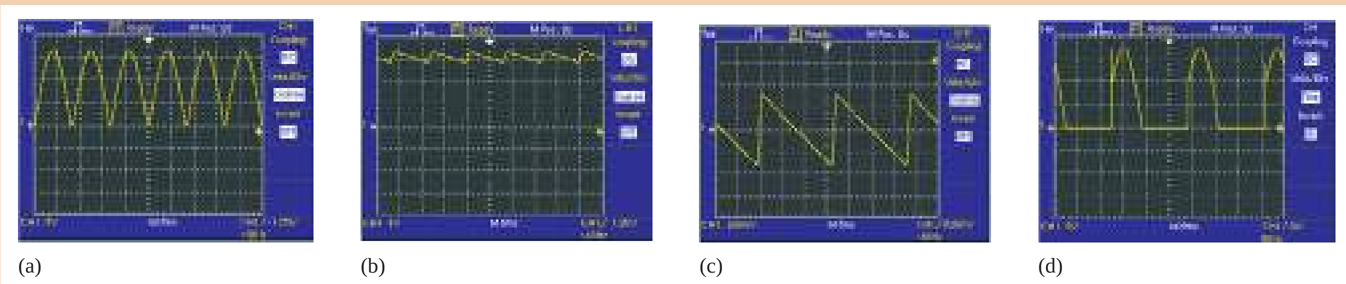


▲ **FIGURE 2–90**

Testing the power supply printed circuit board. The 62 Ω load is a temporary test load to check ripple when the power supply is used at its maximum rated current.

Troubleshooting

For each of the scope output voltage measurements in Figure 2–91, determine the likely fault or faults, if any.

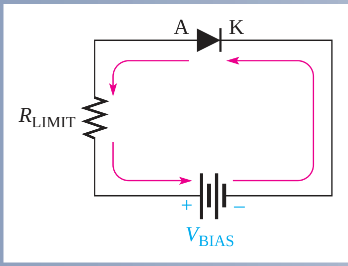


▲ **FIGURE 2–91**

Output voltage measurements on the power supply circuit.

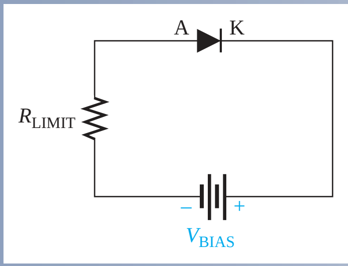
SUMMARY OF DIODE BIAS

FORWARD BIAS: PERMITS MAJORITY-CARRIER CURRENT



- Bias voltage connections: positive to anode (A); negative to cathode (K).
- The bias voltage must be greater than the barrier potential.
- Barrier potential: 0.7 V for silicon.
- Majority carriers provide the forward current.
- The depletion region narrows.

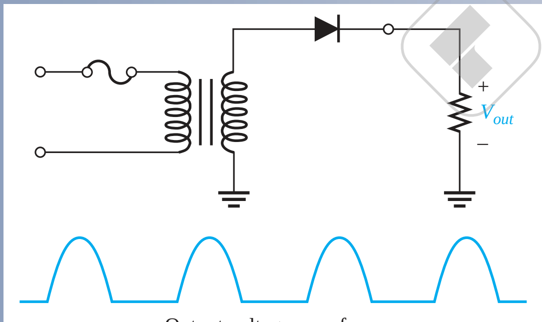
REVERSE BIAS: PREVENTS MAJORITY-CARRIER CURRENT



- Bias voltage connections: positive to cathode (K); negative to anode (A).
- The bias voltage must be less than the breakdown voltage.
- There is no majority carrier current after transition time.
- Minority carriers provide a negligibly small reverse current.
- The depletion region widens.

SUMMARY OF POWER SUPPLY RECTIFIERS

HALF-WAVE RECTIFIER



Output voltage waveform

- Peak value of output:

  $V_{p(out)} = V_{p(sec)} - 0.7\text{ V}$

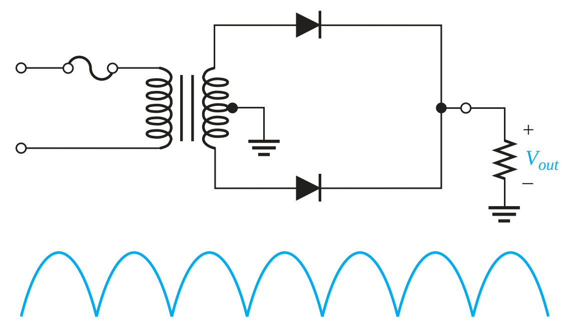
- Average value of output:

  $V_{AVG} = \dfrac{V_{p(out)}}{\pi}$

- Diode peak inverse voltage:

  $\text{PIV} = V_{p(sec)}$

CENTER-TAPPED FULL-WAVE RECTIFIER



Output voltage waveform

- Peak value of output:

  $V_{p(out)} = \dfrac{V_{p(sec)}}{2} - 0.7\text{ V}$

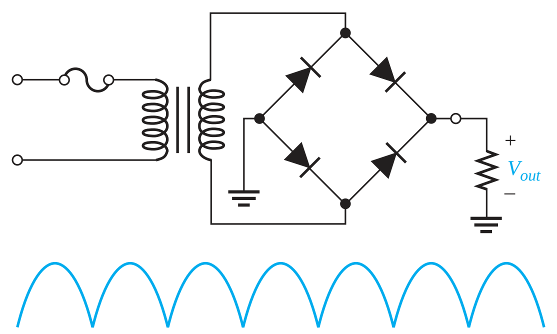
- Average value of output:

  $V_{AVG} = \dfrac{2V_{p(out)}}{\pi}$

- Diode peak inverse voltage:

  $\text{PIV} = 2V_{p(out)} + 0.7\text{ V}$

BRIDGE FULL-WAVE RECTIFIER



Output voltage waveform

- Peak value of output:

$$V_{p(out)} = V_{p(sec)} - 1.4\text{ V}$$

- Average value of output:

$$V_{AVG} = \frac{2V_{p(out)}}{\pi}$$

- Diode peak inverse voltage:

$$\text{PIV} = V_{p(out)} + 0.7\text{ V}$$

SUMMARY

Section 2–1

- There is current through a diode only when it is forward-biased. Ideally, there is no current when there is no bias nor when there is reverse bias. Actually, there is a very small current in reverse bias due to the thermally generated minority carriers, but this can usually be neglected.
- Avalanche occurs in a reverse-biased diode if the bias voltage equals or exceeds the breakdown voltage.
- A diode conducts current when forward-biased and blocks current when reversed-biased.
- Reverse breakdown voltage for a diode is typically greater than 50 V.

Section 2–2

- The *V-I* characteristic curve shows the diode current as a function of voltage across the diode.
- The resistance of a forward-biased diode is called the *dynamic* or *ac resistance.*
- Reverse current increases rapidly at the reverse breakdown voltage.
- Reverse breakdown should be avoided in most diodes.

Section 2–3

- The ideal model represents the diode as a closed switch in forward bias and as an open switch in reverse bias.
- The practical model represents the diode as a switch in series with the barrier potential.
- The complete model includes the dynamic forward resistance in series with the practical model in forward bias and the reverse resistance in parallel with the open switch in reverse bias.

Section 2–4

- A dc power supply typically consists of a transformer, a diode rectifier, a filter, and a regulator.
- The single diode in a half-wave rectifier is forward-biased and conducts for 180° of the input cycle.
- The output frequency of a half-wave rectifier equals the input frequency.
- PIV (peak inverse voltage) is the maximum voltage appearing across the diode in reverse bias.

Section 2–5

- Each diode in a full-wave rectifier is forward-biased and conducts for 180° of the input cycle.
- The output frequency of a full-wave rectifier is twice the input frequency.
- The two basic types of full-wave rectifier are center-tapped and bridge.
- The peak output voltage of a center-tapped full-wave rectifier is approximately one-half of the total peak secondary voltage less one diode drop.
- The PIV for each diode in a center-tapped full-wave rectifier is twice the peak output voltage plus one diode drop.
- The peak output voltage of a bridge rectifier equals the total peak secondary voltage less two diode drops.
- The PIV for each diode in a bridge rectifier is approximately half that required for an equivalent center-tapped configuration and is equal to the peak output voltage plus one diode drop.

Section 2–6
- A capacitor-input filter provides a dc output approximately equal to the peak of its rectified input voltage.
- Ripple voltage is caused by the charging and discharging of the filter capacitor.
- The smaller the ripple voltage, the better the filter.
- Regulation of output voltage over a range of input voltages is called *input* or *line regulation.*
- Regulation of output voltage over a range of load currents is called *load regulation.*

Section 2–7
- Diode limiters cut off voltage above or below specified levels. Limiters are also called *clippers.*
- Diode clampers add a dc level to an ac voltage.

Section 2–8
- Voltage multipliers are used in high-voltage, low-current applications such as for electron beam acceleration in CRTs and for particle accelerators.
- A voltage multiplier uses a series of diode-capacitor stages.
- Input voltage can be doubled, tripled, or quadrupled.

Section 2–9
- A datasheet provides key information about the parameters and characteristics of an electronic device.
- A diode should always be operated below the absolute maximum ratings specified on the datasheet.

Section 2–10
- Many DMMs provide a diode test function.
- DMMs display the diode drop when the diode is operating properly in forward bias.
- Most DMMs indicate "OL" when the diode is open.
- Troubleshooting is the application of logical thought combined with a thorough knowledge of the circuit or system to identify and correct a malfunction.
- Troubleshooting is a three-step process of analysis, planning, and measurement.
- Fault analysis is the isolation of a fault to a particular circuit or portion of a circuit.

KEY TERMS

Key terms and other bold terms in the chapter are defined in the end-of-book glossary.

Bias The application of a dc voltage to a diode to make it either conduct or block current.

Clamper A circuit that adds a dc level to an ac voltage using a diode and a capacitor.

DC power supply A circuit that converts ac line voltage to dc voltage and supplies constant power to operate a circuit or system.

Diode A semiconductor device with a single *pn* junction that conducts current in only one direction.

Filter In a power supply, the capacitor used to reduce the variation of the output voltage from a rectifier.

Forward bias The condition in which a diode conducts current.

Full-wave rectifier A circuit that converts an ac sinusoidal input voltage into a pulsating dc voltage with two output pulses occurring for each input cycle.

Half-wave rectifier A circuit that converts an ac sinusoidal input voltage into a pulsating dc voltage with one output pulse occurring for each input cycle.

Limiter A diode circuit that clips off or removes part of a waveform above and/or below a specified level.

Line regulation The change in output voltage of a regulator for a given change in input voltage, normally expressed as a percentage.

Load regulation The change in output voltage of a regulator for a given range of load currents, normally expressed as a percentage.

Peak inverse voltage (PIV) The maximum value of reverse voltage across a diode that occurs at the peak of the input cycle when the diode is reverse-biased.

Rectifier An electronic circuit that converts ac into pulsating dc; one part of a power supply.

Regulator An electronic device or circuit that maintains an essentially constant output voltage for a range of input voltage or load values; one part of a power supply.

Reverse bias The condition in which a diode prevents current.

Ripple voltage The small variation in the dc output voltage of a filtered rectifier caused by the charging and discharging of the filter capacitor.

Troubleshooting A systematic process of isolating, identifying, and correcting a fault in a circuit or system.

***V-I* characteristic** A curve showing the relationship of diode voltage and current.

KEY FORMULAS

2–1	$I_F = \dfrac{V_{BIAS}}{R_{LIMIT}}$	Forward current, ideal diode model
2–2	$I_F = \dfrac{V_{BIAS} - V_F}{R_{LIMIT}}$	Forward current, practical diode model
2–3	$V_{AVG} = \dfrac{V_p}{\pi}$	Half-wave average value
2–4	$V_{p(out)} = V_{p(in)} - 0.7\text{ V}$	Peak half-wave rectifier output (silicon)
2–5	$\text{PIV} = V_{p(in)}$	Peak inverse voltage, half-wave rectifier
2–6	$V_{AVG} = \dfrac{2V_p}{\pi}$	Full-wave average value
2–7	$V_{out} = \dfrac{V_{sec}}{2} - 0.7\text{ V}$	Center-tapped full-wave output
2–8	$\text{PIV} = 2V_{p(out)} + 0.7\text{ V}$	Peak inverse voltage, center-tapped rectifier
2–9	$V_{p(out)} = V_{p(sec)} - 1.4\text{ V}$	Bridge full-wave output
2–10	$\text{PIV} = V_{p(out)} + 0.7\text{ V}$	Peak inverse voltage, bridge rectifier
2–11	$r = \dfrac{V_{r(pp)}}{V_{DC}}$	Ripple factor
2–12	$V_{r(pp)} \cong \left(\dfrac{1}{fR_LC}\right)V_{p(rect)}$	Peak-to-peak ripple voltage, capacitor-input filter
2–13	$V_{DC} = \left(1 - \dfrac{1}{2fR_LC}\right)V_{p(rect)}$	DC output voltage, capacitor-input filter
2–14	$\text{Line regulation} = \left(\dfrac{\Delta V_{OUT}}{\Delta V_{IN}}\right)100\%$	
2–15	$\text{Load regulation} = \left(\dfrac{V_{NL} - V_{FL}}{V_{FL}}\right)100\%$	

TRUE/FALSE QUIZ

Answers can be found at www.pearsonhighered.com/floyd.

1. The two regions of a diode are the anode and the collector.
2. A diode can conduct current in two directions with equal ease.
3. A diode conducts current when forward-biased.
4. When reverse-biased, a diode ideally appears as a short.
5. Two types of current in a diode are electron and hole.
6. A basic half-wave rectifier consists of one diode.
7. The output frequency of a half-wave rectifier is twice the input frequency.
8. The diode in a half-wave rectifier conducts for half the input cycle.
9. PIV stands for positive inverse voltage.
10. Each diode in a full-wave rectifier conducts for the entire input cycle.
11. The output frequency of a full-wave rectifier is twice the input frequency.
12. A bridge rectifier uses four diodes.
13. In a bridge rectifier, two diodes conduct during each half cycle of the input.
14. The purpose of the capacitor filter in a rectifier is to convert ac to dc.
15. The output voltage of a filtered rectifier always has some ripple voltage.

16. A smaller filter capacitor reduces the ripple.
17. Line and load regulation are the same.
18. A diode limiter is also known as a clipper.
19. The purpose of a clamper is to remove a dc level from a waveform.
20. Voltage multipliers use diodes and capacitors.

CIRCUIT-ACTION QUIZ

Answers can be found at www.pearsonhighered.com/floyd.

1. When a diode is forward-biased and the bias voltage is increased, the forward current will
   (a) increase **(b)** decrease **(c)** not change
2. When a diode is forward-biased and the bias voltage is increased, the voltage across the diode (assuming the practical model) will
   (a) increase **(b)** decrease **(c)** not change
3. When a diode is reverse-biased and the bias voltage is increased, the reverse current (assuming the practical model) will
   (a) increase **(b)** decrease **(c)** not change
4. When a diode is reverse-biased and the bias voltage is increased, the reverse current (assuming the complete model) will
   (a) increase **(b)** decrease **(c)** not change
5. When a diode is forward-biased and the bias voltage is increased, the voltage across the diode (assuming the complete model) will
   (a) increase **(b)** decrease **(c)** not change
6. If the forward current in a diode is increased, the diode voltage (assuming the practical model) will
   (a) increase **(b)** decrease **(c)** not change
7. If the forward current in a diode is decreased, the diode voltage (assuming the complete model) will
   (a) increase **(b)** decrease **(c)** not change
8. If the barrier potential of a diode is exceeded, the forward current will
   (a) increase **(b)** decrease **(c)** not change
9. If the input voltage in Figure 2–28 is increased, the peak inverse voltage across the diode will
   (a) increase **(b)** decrease **(c)** not change
10. If the turns ratio of the transformer in Figure 2–28 is decreased, the forward current through the diode will
   (a) increase **(b)** decrease **(c)** not change
11. If the frequency of the input voltage in Figure 2–36 is increased, the output voltage will
   (a) increase **(b)** decrease **(c)** not change
12. If the PIV rating of the diodes in Figure 2–36 is increased, the current through R_L will
   (a) increase **(b)** decrease **(c)** not change
13. If one of the diodes in Figure 2–41 opens, the average voltage to the load will
   (a) increase **(b)** decrease **(c)** not change
14. If the value of R_L in Figure 2–41 is decreased, the current through each diode will
   (a) increase **(b)** decrease **(c)** not change
15. If the capacitor value in Figure 2–48 is decreased, the output ripple voltage will
   (a) increase **(b)** decrease **(c)** not change
16. If the line voltage in Figure 2–51 is increased, ideally the +5 V output will
   (a) increase **(b)** decrease **(c)** not change
17. If the bias voltage in Figure 2–55 is decreased, the positive portion of the output voltage will
   (a) increase **(b)** decrease **(c)** not change
18. If the bias voltage in Figure 2–55 is increased, the negative portion of the output voltage will
   (a) increase **(b)** decrease **(c)** not change

19. If the value of R_3 in Figure 2–61 is decreased, the positive output voltage will
(a) increase **(b)** decrease **(c)** not change

20. If the input voltage in Figure 2–65 is increased, the peak negative value of the output voltage will
(a) increase **(b)** decrease **(c)** not change

SELF-TEST

Answers can be found at www.pearsonhighered.com/floyd.

Section 2–1

1. The term *bias* means
(a) the ratio of majority carriers to minority carriers
(b) the amount of current across a diode
(c) a dc voltage is applied to control the operation of a device
(d) neither (a), (b), nor (c)

2. To forward-bias a diode,
(a) an external voltage is applied that is positive at the anode and negative at the cathode
(b) an external voltage is applied that is negative at the anode and positive at the cathode
(c) an external voltage is applied that is positive at the *p* region and negative at the *n* region
(d) answers (a) and (c)

3. When a diode is forward-biased,
(a) the only current is hole current
(b) the only current is electron current
(c) the only current is produced by majority carriers
(d) the current is produced by both holes and electrons

4. Although current is blocked in reverse bias,
(a) there is some current due to majority carriers
(b) there is a very small current due to minority carriers
(c) there is an avalanche current

5. For a silicon diode, the value of the forward-bias voltage typically
(a) must be greater than 0.3 V
(b) must be greater than 0.7 V
(c) depends on the width of the depletion region
(d) depends on the concentration of majority carriers

6. When forward-biased, a diode
(a) blocks current **(b)** conducts current
(c) has a high resistance **(d)** drops a large voltage

Section 2–2

7. A diode is normally operated in
(a) reverse breakdown **(b)** the forward-bias region
(c) the reverse-bias region **(d)** either (b) or (c)

8. The dynamic resistance can be important when a diode is
(a) reverse-biased **(b)** forward-biased
(c) in reverse breakdown **(d)** unbiased

9. The *V-I* curve for a diode shows
(a) the voltage across the diode for a given current
(b) the amount of current for a given bias voltage
(c) the power dissipation
(d) none of these

Section 2–3

10. Ideally, a diode can be represented by a
(a) voltage source **(b)** resistance **(c)** switch **(d)** all of these

11. In the practical diode model,
(a) the barrier potential is taken into account
(b) the forward dynamic resistance is taken into account
(c) none of these
(d) both (a) and (b)

12. In the complete diode model,
(a) the barrier potential is taken into account
(b) the forward dynamic resistance is taken into account
(c) the reverse resistance is taken into account
(d) all of these

Section 2–4

13. The average value of a half-wave rectified voltage with a peak value of 200 V is
(a) 63.7 V **(b)** 127.2 V **(c)** 141 V **(d)** 0 V

14. When a 60 Hz sinusoidal voltage is applied to the input of a half-wave rectifier, the output frequency is
(a) 120 Hz **(b)** 30 Hz **(c)** 60 Hz **(d)** 0 Hz

15. The peak value of the input to a half-wave rectifier is 10 V. The approximate peak value of the output is
(a) 10 V **(b)** 3.18 V **(c)** 10.7 V **(d)** 9.3 V

16. For the circuit in Question 15, the diode must be able to withstand a reverse voltage of
(a) 10 V **(b)** 5 V **(c)** 20 V **(d)** 3.18 V

Section 2–5

17. The average value of a full-wave rectified voltage with a peak value of 75 V is
(a) 53 V **(b)** 47.8 V **(c)** 37.5 V **(d)** 23.9 V

18. When a 60 Hz sinusoidal voltage is applied to the input of a full-wave rectifier, the output frequency is
(a) 120 Hz **(b)** 60 Hz **(c)** 240 Hz **(d)** 0 Hz

19. The total secondary voltage in a center-tapped full-wave rectifier is 125 V rms. Neglecting the diode drop, the rms output voltage is
(a) 125 V **(b)** 177 V **(c)** 100 V **(d)** 62.5 V

20. When the peak output voltage is 100 V, the PIV for each diode in a center-tapped full-wave rectifier is (neglecting the diode drop)
(a) 100 V **(b)** 200 V **(c)** 141 V **(d)** 50 V

21. When the rms output voltage of a bridge full-wave rectifier is 20 V, the peak inverse voltage across the diodes is (neglecting the diode drop)
(a) 20 V **(b)** 40 V **(c)** 28.3 V **(d)** 56.6 V

Section 2–6

22. The ideal dc output voltage of a capacitor-input filter is equal to
(a) the peak value of the rectified voltage
(b) the average value of the rectified voltage
(c) the rms value of the rectified voltage

23. A certain power-supply filter produces an output with a ripple of 100 mV peak-to-peak and a dc value of 20 V. The ripple factor is
(a) 0.05 **(b)** 0.005 **(c)** 0.00005 **(d)** 0.02

24. A 60 V peak full-wave rectified voltage is applied to a capacitor-input filter. If $f = 120$ Hz, $R_L = 10\ \text{k}\Omega$, and $C = 10\ \mu\text{F}$, the ripple voltage is
(a) 0.6 V **(b)** 6 mV **(c)** 5.0 V **(d)** 2.88 V

25. If the load resistance of a capacitor-filtered full-wave rectifier is reduced, the ripple voltage
(a) increases **(b)** decreases **(c)** is not affected **(d)** has a different frequency

26. Line regulation is determined by
(a) load current
(b) zener current and load current

(c) changes in load resistance and output voltage
(d) changes in output voltage and input voltage

27. Load regulation is determined by
   (a) changes in load current and input voltage
   (b) changes in load current and output voltage
   (c) changes in load resistance and input voltage
   (d) changes in zener current and load current

Section 2–7

28. A 10 V peak-to-peak sinusoidal voltage is applied across a silicon diode and series resistor. The maximum voltage across the diode is
   (a) 9.3 V **(b)** 5 V **(c)** 0.7 V **(d)** 10 V **(e)** 4.3 V
29. In a certain biased limiter, the bias voltage is 5 V and the input is a 10 V peak sine wave. If the positive terminal of the bias voltage is connected to the cathode of the diode, the maximum voltage at the anode is
   (a) 10 V **(b)** 5 V **(c)** 5.7 V **(d)** 0.7 V
30. In a certain positive clamper circuit, a 120 V rms sine wave is applied to the input. The dc value of the output is
   (a) 119.3 V **(b)** 169 V **(c)** 60 V **(d)** 75.6 V

Section 2–8

31. The input of a voltage doubler is 120 V rms. The peak-to-peak output is approximately
   (a) 240 V **(b)** 60 V **(c)** 167 V **(d)** 339 V
32. If the input voltage to a voltage tripler has an rms value of 12 V, the dc output voltage is approximately
   (a) 36 V **(b)** 50.9 V **(c)** 33.9 V **(d)** 32.4 V

Section 2–10

33. When a silicon diode is working properly in forward bias, a DMM in the diode test position will indicate
   (a) 0 V **(b)** OL **(c)** approximately 0.7 V **(d)** approximately 0.3 V
34. When a silicon diode is open, a DMM will generally indicate
   (a) 0 V **(b)** OL **(c)** approximately 0.7 V **(d)** approximately 0.3 V
35. In a rectifier circuit, if the secondary winding in the transformer opens, the output is
   (a) 0 V **(b)** 120 V **(c)** less than it should be **(d)** unaffected
36. If one of the diodes in a bridge full-wave rectifier opens, the output is
   (a) 0 V **(b)** one-fourth the amplitude of the input voltage
   (c) a half-wave rectified voltage **(d)** a 120 Hz voltage
37. If you are checking a 60 Hz full-wave bridge rectifier and observe that the output has a 60 Hz ripple,
   (a) the circuit is working properly **(b)** there is an open diode
   (c) the transformer secondary is shorted **(d)** the filter capacitor is leaky

PROBLEMS

Answers to all odd-numbered problems are at the end of the book.

BASIC PROBLEMS

Section 2–1

Diode Operation

1. To forward-bias a diode, to which region must the positive terminal of a voltage source be connected?
2. Explain why a series resistor is necessary when a diode is forward-biased.

Section 2–2

Voltage-Current Characteristic of a Diode

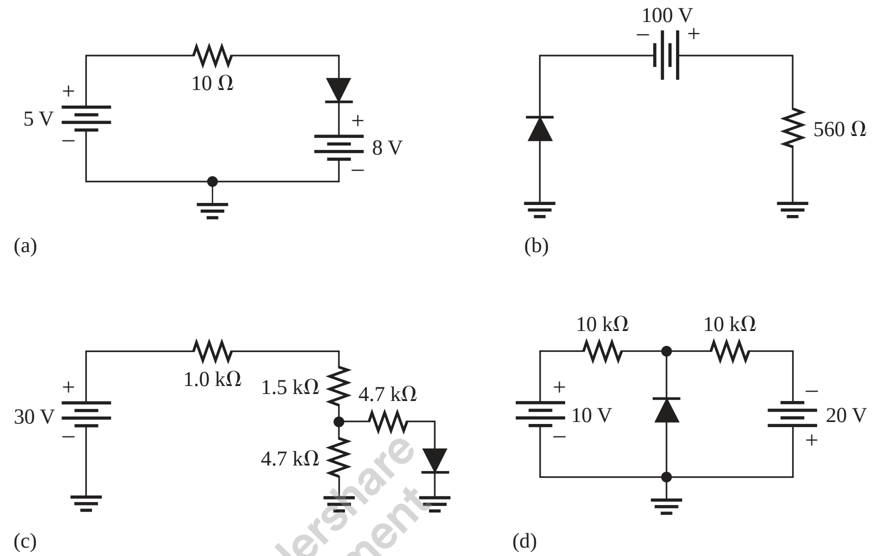
3. Explain how to generate the forward-bias portion of the characteristic curve.
4. What would cause the barrier potential of a silicon diode to decrease from 0.7 V to 0.6 V?

Section 2–3 Diode Models

5. Determine whether each silicon diode in Figure 2–92 is forward-biased or reverse-biased.
6. Determine the voltage across each diode in Figure 2–92, assuming the practical model.
7. Determine the voltage across each diode in Figure 2–92, assuming an ideal diode.
8. Determine the voltage across each diode in Figure 2–92, using the complete diode model with $r'_d = 10\ \Omega$ and $r'_R = 100\ \text{M}\Omega$.

▶ FIGURE 2–92

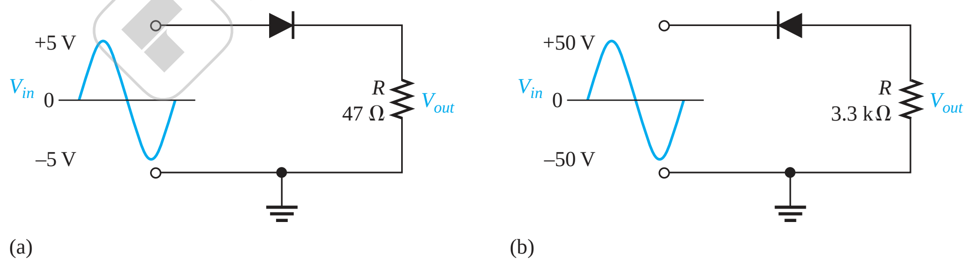
Multisim file circuits are identified with a logo and are in the Problems folder on the companion website. Filenames correspond to figure numbers (e.g., F02-92).



Section 2–4 Half-Wave Rectifiers

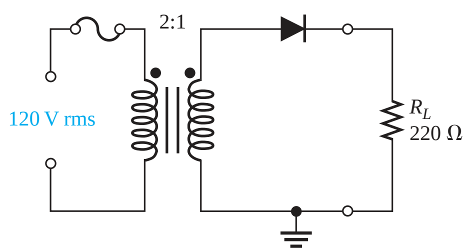
9. Draw the output voltage waveform for each circuit in Figure 2–93 and include the voltage values.

▶ FIGURE 2–93



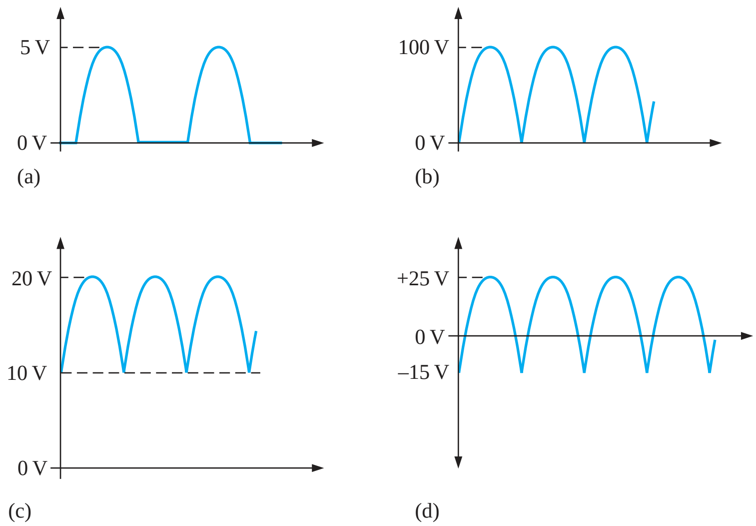
10. What is the peak inverse voltage across each diode in Figure 2–93?
11. Calculate the average value of a half-wave rectified voltage with a peak value of 200 V.
12. What is the peak forward current through each diode in Figure 2–93?
13. A power-supply transformer has a turns ratio of 5:1. What is the secondary voltage if the primary is connected to a 120 V rms source?
14. Determine the peak and average power delivered to R_L in Figure 2–94.

▶ FIGURE 2–94



Section 2–5 Full-Wave Rectifiers

15. Find the average value of each voltage in Figure 2–95.



▲ FIGURE 2–95

16. Consider the circuit in Figure 2–96.

(a) What type of circuit is this?

(b) What is the total peak secondary voltage?

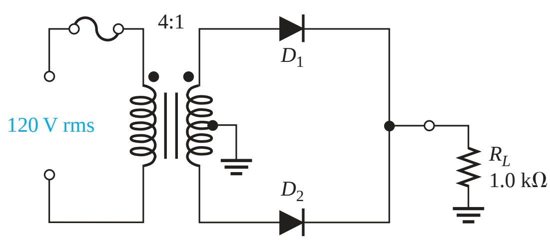
(c) Find the peak voltage across each half of the secondary.

(d) Sketch the voltage waveform across R_L.

(e) What is the peak current through each diode?

(f) What is the PIV for each diode?

► FIGURE 2–96



17. Calculate the peak voltage across each half of a center-tapped transformer used in a full-wave rectifier that has an average output voltage of 120 V.

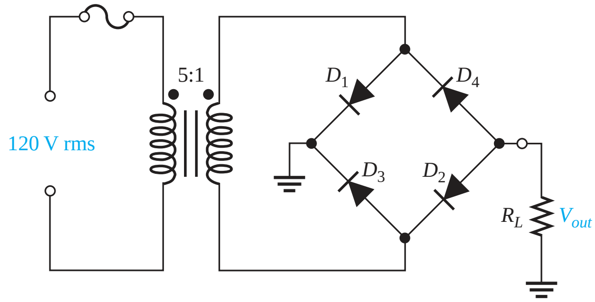
18. Show how to connect the diodes in a center-tapped rectifier in order to produce a negative-going full-wave voltage across the load resistor.

19. What PIV rating is required for the diodes in a bridge rectifier that produces an average output voltage of 50 V?

20. The rms output voltage of a bridge rectifier is 20 V. What is the peak inverse voltage across the diodes?

21. Draw the output voltage waveform for the bridge rectifier in Figure 2–97. Notice that all the diodes are reversed from circuits shown earlier in the chapter.

▶ FIGURE 2–97



Section 2–6 Power Supply Filters and Regulators

22. A certain rectifier filter produces a dc output voltage of 75 V with a peak-to-peak ripple voltage of 0.5 V. Calculate the ripple factor.

23. A certain full-wave rectifier has a peak output voltage of 30 V. A 50 μF capacitor-input filter is connected to the rectifier. Calculate the peak-to-peak ripple and the dc output voltage developed across a 600 Ω load resistance.

24. What is the percentage of ripple for the rectifier filter in Problem 23?

25. What value of filter capacitor is required to produce a 1% ripple factor for a full-wave rectifier having a load resistance of 1.5 kΩ? Assume the rectifier produces a peak output of 18 V.

26. A full-wave rectifier produces an 80 V peak rectified voltage from a 60 Hz ac source. If a 10 μF filter capacitor is used, determine the ripple factor for a load resistance of 10 kΩ.

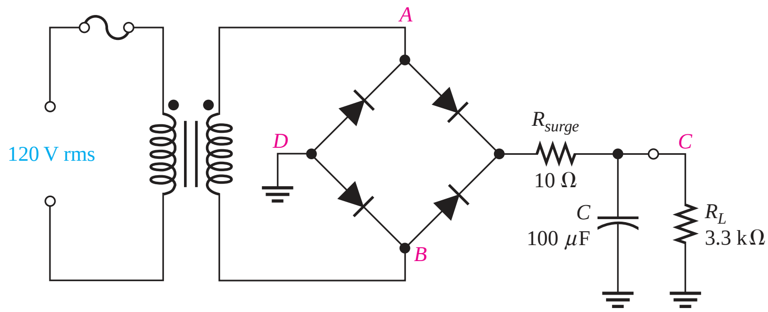
27. Determine the peak-to-peak ripple and dc output voltages in Figure 2–98. The transformer has a 36 V rms secondary voltage rating, and the line voltage has a frequency of 60 Hz.

28. Refer to Figure 2–98 and draw the following voltage waveforms in relationship to the input waveforms: V_{AB}, V_{AD}, and V_{CD}. A double letter subscript indicates a voltage from one point to another.

29. If the no-load output voltage of a regulator is 15.5 V and the full-load output is 14.9 V, what is the percent load regulation?

30. Assume a regulator has a percent load regulation of 0.5%. What is the output voltage at full-load if the unloaded output is 12.0 V?

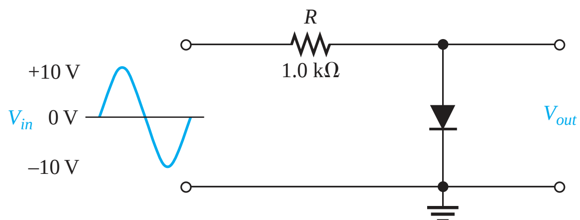
▶ FIGURE 2–98



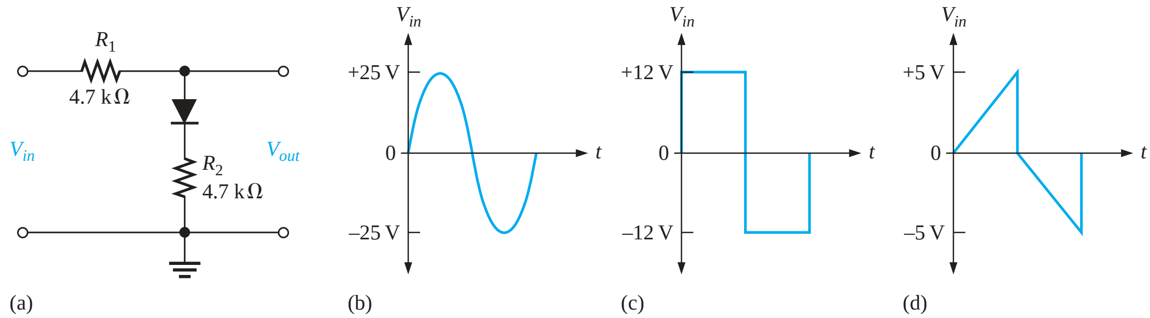
Section 2–7 Diode Limiters and Clampers

31. Determine the output waveform for the circuit of Figure 2–99.

▶ FIGURE 2–99

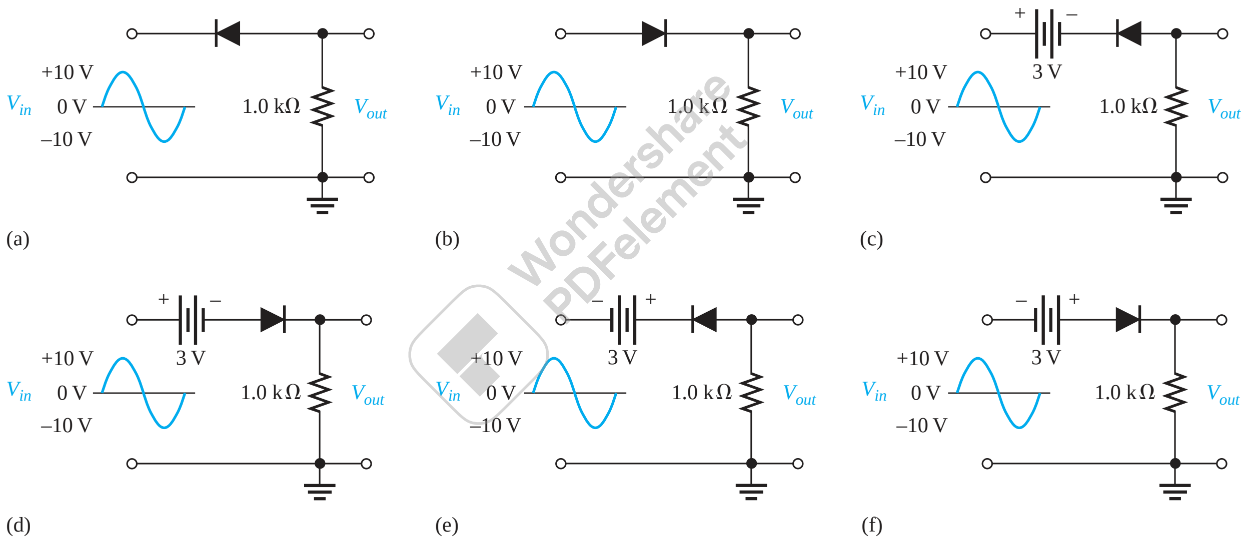


32. Determine the output voltage for the circuit in Figure 2–100(a) for each input voltage in (b), (c), and (d).



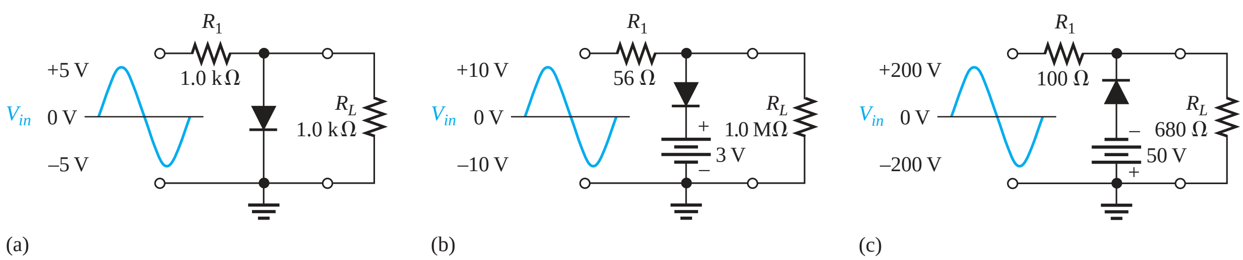
▲ FIGURE 2–100

33. Determine the output voltage waveform for each circuit in Figure 2–101.



▲ FIGURE 2–101

34. Determine the R_L voltage waveform for each circuit in Figure 2–102.

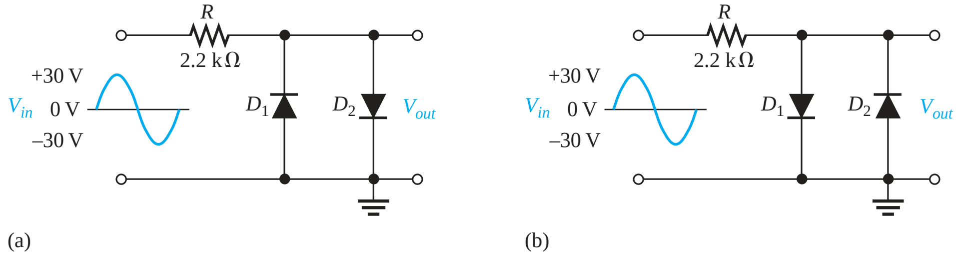


▲ FIGURE 2–102

35. Draw the output voltage waveform for each circuit in Figure 2–103.

36. Determine the peak forward current through each diode in Figure 2–103.

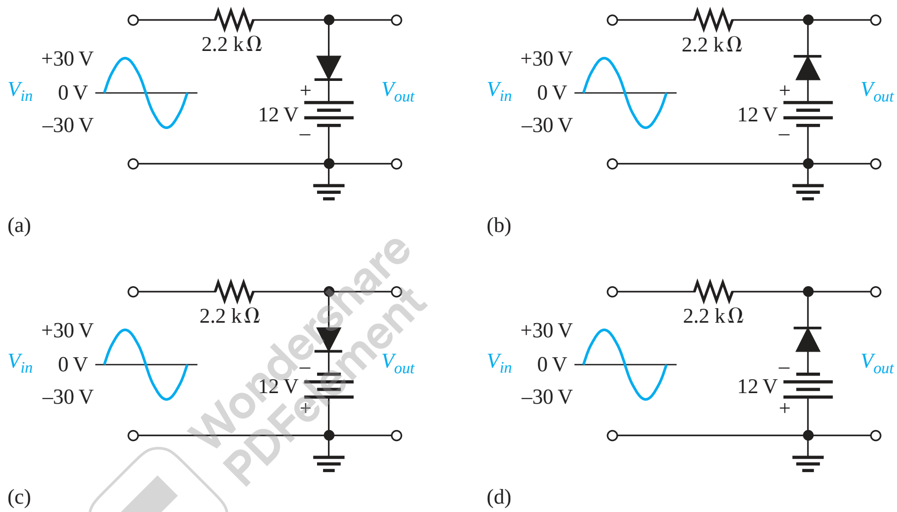
▶ FIGURE 2–103



37. Determine the peak forward current through each diode in Figure 2–104.

38. Determine the output voltage waveform for each circuit in Figure 2–104.

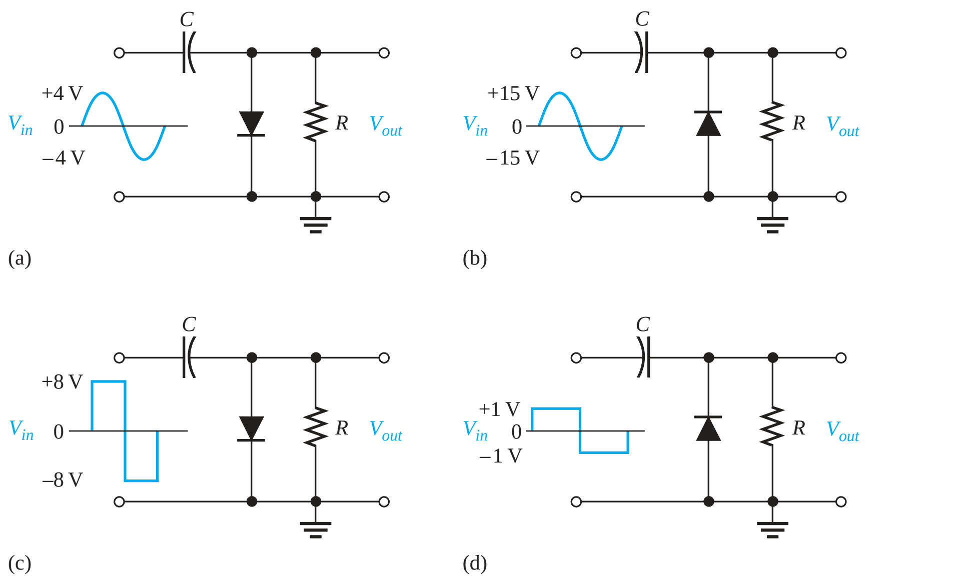
▶ FIGURE 2–104



39. Describe the output waveform of each circuit in Figure 2–105. Assume the *RC* time constant is much greater than the period of the input.

40. Repeat Problem 39 with the diodes turned around.

▶ FIGURE 2–105



Section 2–8 **Voltage Multipliers**

41. A certain voltage doubler has 20 V rms on its input. What is the output voltage? Draw the circuit, indicating the output terminals and PIV rating for the diode.

42. Repeat Problem 41 for a voltage tripler and quadrupler.

Section 2–9 **The Diode Datasheet**

43. From the datasheet in Figure 2–71, determine how much peak inverse voltage that a 1N4002 diode can withstand.

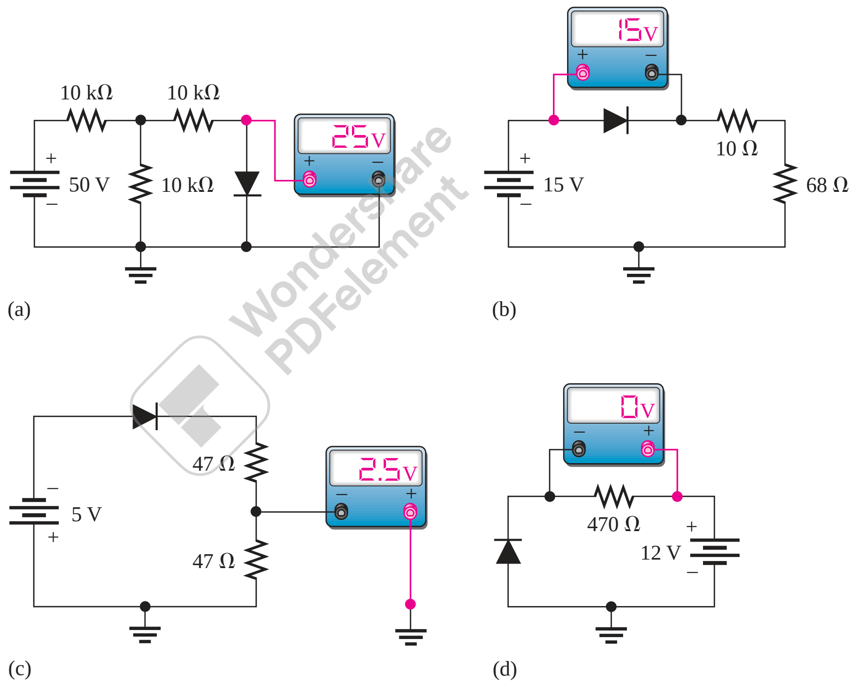
44. Repeat Problem 43 for a 1N4007.

45. If the peak output voltage of a bridge full-wave rectifier is 50 V, determine the minimum value of the load resistance that can be used when 1N4002 diodes are used.

Section 2–10 **Troubleshooting**

46. Consider the meter indications in each circuit of Figure 2–106, and determine whether the diode is functioning properly, or whether it is open or shorted. Assume the ideal model.

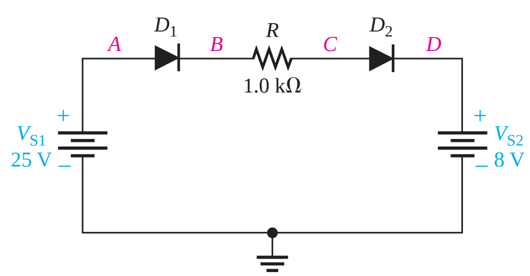
▶ FIGURE 2–106



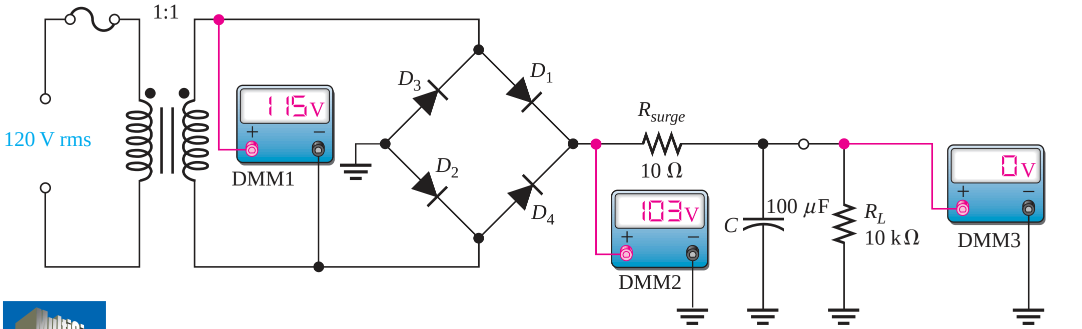
47. Determine the voltage with respect to ground at each point in Figure 2–107. Assume the practical model.

48. If one of the diodes in a bridge rectifier opens, what happens to the output?

▶ FIGURE 2–107

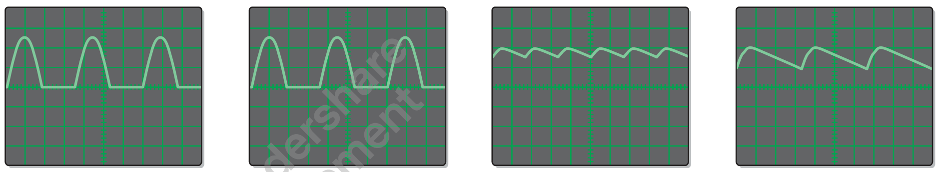


49. From the meter readings in Figure 2–108, determine if the rectifier is functioning properly. If it is not, determine the most likely failure(s).



▲ **FIGURE 2–108**

50. Each part of Figure 2–109 shows oscilloscope displays of various rectifier output voltages. In each case, determine whether or not the rectifier is functioning properly and if it is not, determine the most likely failure(s).

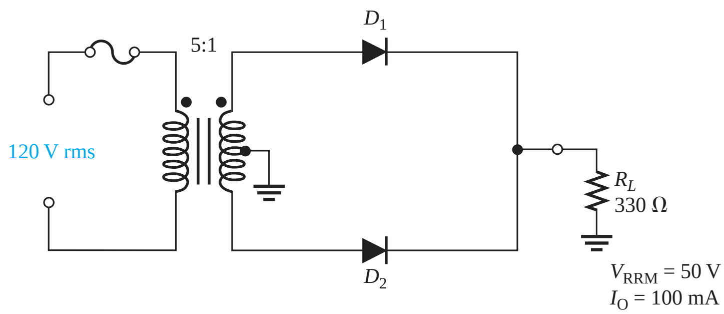


(a) Output of a half-wave unfiltered rectifier
(b) Output of a full-wave unfiltered rectifier
(c) Output of a full-wave filter
(d) Output of same full-wave filter as part (c)

▲ **FIGURE 2–109**

51. Based on the values given, would you expect the circuit in Figure 2–110 to fail? If so, why?

▶ **FIGURE 2–110**



APPLICATION ACTIVITY PROBLEMS

52. Determine the most likely failure(s) in the circuit of Figure 2–111 for each of the following symptoms. State the corrective action you would take in each case. The transformer has a rated output of 10 V rms.

(a) No voltage from test point 1 to test point 2

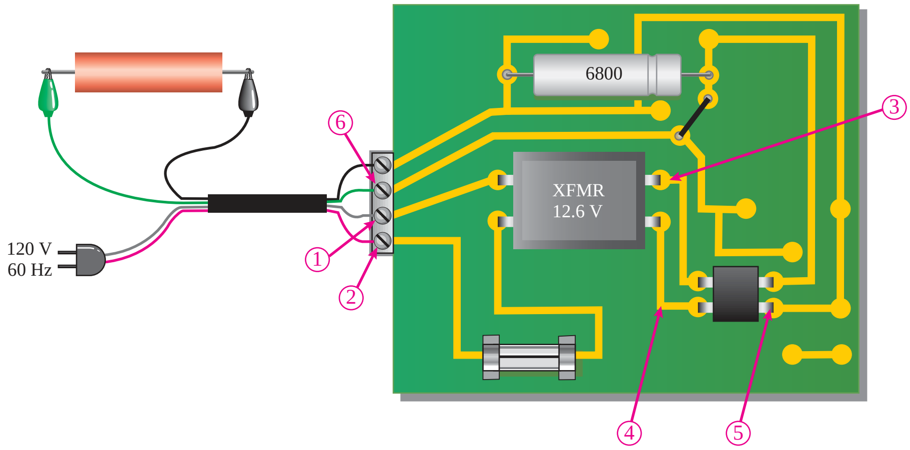
(b) No voltage from test point 3 to test point 4

(c) 8 V rms from test point 3 to test point 4

(d) Excessive 120 Hz ripple voltage at test point 6

(e) There is a 60 Hz ripple voltage at test point 6

(f) No voltage at test point 6



▲ FIGURE 2–111

53. In testing the power supply circuit in Figure 2–111 with a 10 kΩ load resistor connected, you find the voltage at the positive side of the filter capacitor to have a 60 Hz ripple voltage. You replace the bridge rectifier and check the point again but it still has the 60 Hz ripple. What now?

54. Suppose the bridge rectifier in Figure 2–111 is connected backwards such that the transformer secondary is now connected to the output pins instead of the input pins. What will be observed at test point 6?

ADVANCED PROBLEMS

55. A full-wave rectifier with a capacitor-input filter provides a dc output voltage of 35 V to a 3.3 kΩ load. Determine the minimum value of filter capacitor if the maximum peak-to-peak ripple voltage is to be 0.5 V.

56. A certain unfiltered full-wave rectifier with 120 V, 60 Hz input produces an output with a peak of 15 V. When a capacitor-input filter and a 1.0 kΩ load are connected, the dc output voltage is 14 V. What is the peak-to-peak ripple voltage?

57. For a certain full-wave rectifier, the measured surge current in the capacitor filter is 50 A. The transformer is rated for a secondary voltage of 24 V with a 120 V, 60 Hz input. Determine the value of the surge resistor in this circuit.

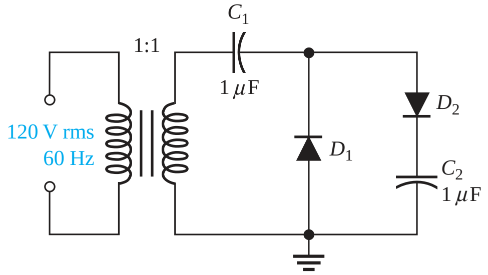
58. Design a full-wave rectifier using an 18 V center-tapped transformer. The output ripple is not to exceed 5% of the output voltage with a load resistance of 680 Ω. Specify the $I_{F(AV)}$ and PIV ratings of the diodes and select an appropriate diode from the datasheet in Figure 2–71.

59. Design a filtered power supply that can produce dc output voltages of +9 V ± 10% and −9 V ± 10% with a maximum load current of 100 mA. The voltages are to be switch selectable across one set of output terminals. The ripple voltage must not exceed 0.25 V rms.

60. Design a circuit to limit a 20 V rms sinusoidal voltage to a maximum positive amplitude of 10 V and a maximum negative amplitude of −5 V using a single 14 V dc voltage source.

61. Determine the voltage across each capacitor in the circuit of Figure 2–112.

► FIGURE 2–112



MULTISIM TROUBLESHOOTING PROBLEMS

These file circuits are in the Troubleshooting Problems folder on the companion website.

62. Open file TSP02-62 and determine the fault.

63. Open file TSP02-63 and determine the fault.

64. Open file TSP02-64 and determine the fault.

65. Open file TSP02-65 and determine the fault.

66. Open file TSP02-66 and determine the fault.

67. Open file TSP02-67 and determine the fault.

68. Open file TSP02-68 and determine the fault.

69. Open file TSP02-69 and determine the fault.

70. Open file TSP02-70 and determine the fault.

71. Open file TSP02-71 and determine the fault.

72. Open file TSP02-72 and determine the fault.

73. Open file TSP02-73 and determine the fault.

74. Open file TSP02-74 and determine the fault.

75. Open file TSP02-75 and determine the fault.

76. Open file TSP02-76 and determine the fault.

77. Open file TSP02-77 and determine the fault.

78. Open file TSP02-78 and determine the fault.

79. Open file TSP02-79 and determine the fault.

GreenTech Application 2: *Solar Power*

In GreenTech Application 1, the photovoltaic cell and a basic solar power system were introduced. The block diagram is shown again in Figure GA2–1. You learned that the basic components of a solar-powered system were the solar panel, the charge controller, the batteries, and the inverter. Now we will continue the solar power coverage by focusing on the charge controller and batteries.

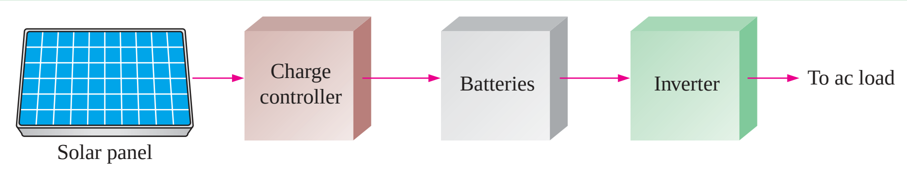


FIGURE GA2–1

The Batteries

Deep-cycle (deep discharge) sealed lead-acid batteries are the most common batteries in solar power systems because their initial cost is lower and they are readily available. Unlike automobile batteries, which are shallow-cycle, deep-cycle batteries can be repeatedly discharged by as much as 80 percent of their capacity, although they will have a longer life if the cycles are shallower.

Deep-cycle batteries are required in solar power systems simply because the sunlight is not at its maximum all of the time—it is an intermittent energy source. When the light intensity from the sun decreases because of clouds or goes away entirely at night, the output from a solar panel drops drastically or goes to zero. During the periods of low light or no light, the batteries will discharge significantly when a load is connected. Typically, the voltage output of a solar panel must be at least 13.6 V to charge a 12 V battery. Solar panels are usually rated at voltages higher than the nominal output. For example, most 12 V solar panels produce 16 V to 20 V at optimal light conditions. The higher voltage outputs are necessary so that the solar panel will still produce a sufficient charging voltage during some nonoptimal conditions.

Battery Connections Batteries can be connected in series to increase the output voltage and in parallel to increase the ampere-hour capacity, as illustrated in Figure GA2–2 for any number of batteries. Several series connections of batteries can be connected in parallel to achieve both an increase in amp-hrs and output voltage. For example, assume a system uses 12 V, 200 Ah batteries. If the system requires 12 V and 600 Ah, three parallel-connected batteries are used. If the system requires 24 V and 200 Ah, two series-connected batteries are used. If 24 V and 600 Ah are needed, three pairs of series batteries are connected in parallel.

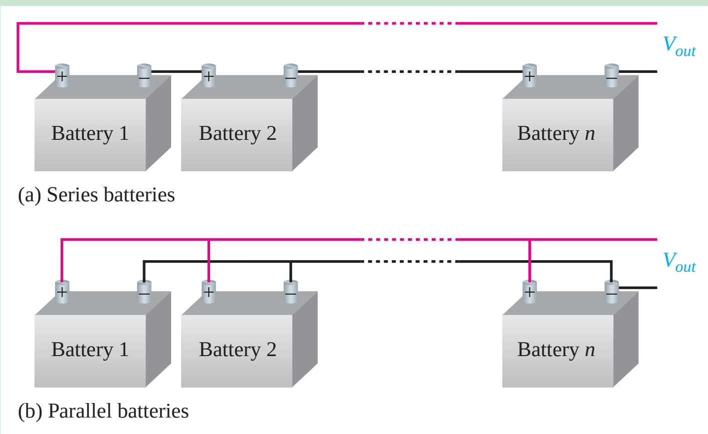


FIGURE GA2–2

The Charge Controller

A solar charge controller is needed in solar power systems that use batteries to store the energy, with the exception of very low-power systems. The solar charge controller regulates the power from the solar panels primarily to prevent overcharging the batteries. Overcharging batteries reduce battery life and may damage the batteries.

Generally, there is no need for a charge controller with trickle-charge solar panels, such as those that produce five watts or less. A good rule-of-thumb is that if the solar panel produces about two watts or less for each 50 battery amp-hrs (Ah), then you don't need one. A charge controller is required if the solar panel produces more than two watts for each 50 Ah of battery rating. For example, a 12 V battery rated at 120 Ah will not require a charge controller, as the following calculation shows, because the solar power is less than 5 W.

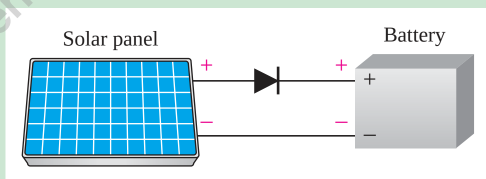
$$\left(\frac{\text{Specified Ah}}{50\text{ Ah}}\right)2\text{ W} = \text{Solar panel power}$$

$$\left(\frac{120\text{ Ah}}{50\text{ Ah}}\right)2\text{ W} = (2.4)2\text{ W} = \mathbf{4.8\ W}$$

In this case, the charging circuit is shown in Figure GA2–3. The diode prevents the battery from discharging back through the solar panel when the panel voltage drops below the battery voltage. For example, when the solar panel is producing 16 V, the diode is forward-biased and the battery is charging. When the battery voltage is 12 V and the panel output drops to less than 12.7 V, the diode is reverse-biased and the battery cannot discharge back through the solar cells.

▶ FIGURE GA2–3

Simple trickle charging in a small solar system (less than 5 W).

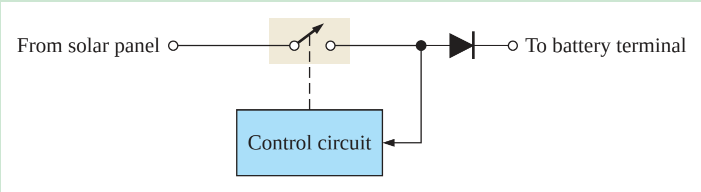


For solar systems of more than about 5 W, a charge controller is necessary. Basically, charge controllers regulate the 16–20 V output of the typical 12 V solar panel down to what the battery needs depending on the amount of battery charge, the type of battery, and the temperature. Solar panels produce more voltage at cooler temperatures.

Types of Charge Controllers Three basic types of charge controllers are on/off, PWM, and MPPT. The most basic controller is the *on/off* type, which simply monitors the battery voltage and stops the charging when the battery voltage reaches a specified level in order to prevent overcharging. It then restarts the charging once the battery voltage drops below a predetermined value. Figure GA2–4 shows the basic concept. The switch shown represents a transistor that is turned on and off. (You will study transistors beginning in Chapter 4.) The voltage of the battery is fed back to the control circuit. When the voltage is below a set low value, the control circuit turns the switch *on* to charge the battery. When the battery charges to a set high value, the control circuit turns the switch *off*. The diode prevents discharge back through the control circuit when the output of the panel is lower than the battery.

▶ FIGURE GA2–4

Basic concept of the on/off charge controller.



PWM (pulse width modulation) charge controllers gradually reduce the amount of power applied to the batteries as the batteries get closer to full charge. This type of controller allows the batteries to be more fully charged with less stress on the batteries. This extends the life of the batteries and constantly maintains the batteries in a fully charged state (called "float") during sunlight hours. The PWM controller produces a series of pulses to charge the batteries instead of a constant charge. The battery voltage is constantly monitored to determine how to adjust the frequency of the pulses and the pulse widths. When the batteries are fully charged and there is no load to drain them, the controller produces very short pulses at a low rate or no pulses at all. When the batteries are discharged, long pulses at a high rate are sent or the controller may go into a constant-charging mode, depending on the amount of discharge.

Figure GA2–5 shows the basic concept of a PWM charge controller. In part (a), the PWM and control circuit produces pulses based on the input from the sampling circuit. The sampling circuit determines the actual battery voltage by sampling the voltage between pulses. The diode acts as a rectifier and also blocks discharge of the battery back through the charger at night. Part (b) demonstrates how the battery charges during each pulse and how the width and the time between pulses change as the battery charges.

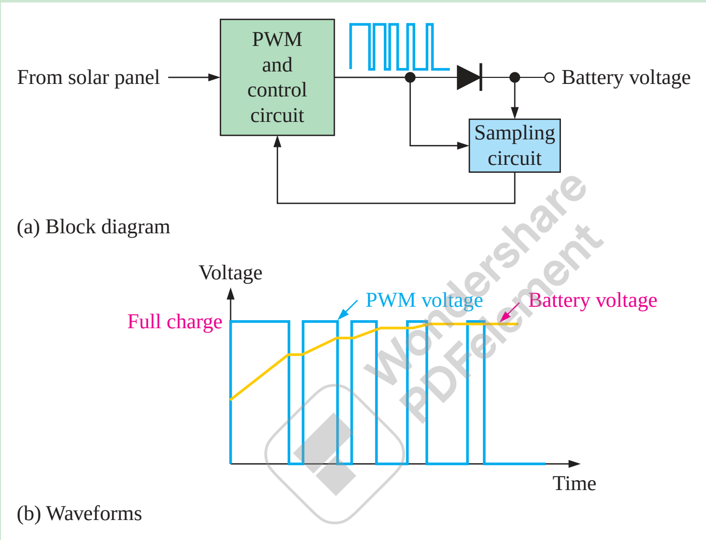


FIGURE GA2–5

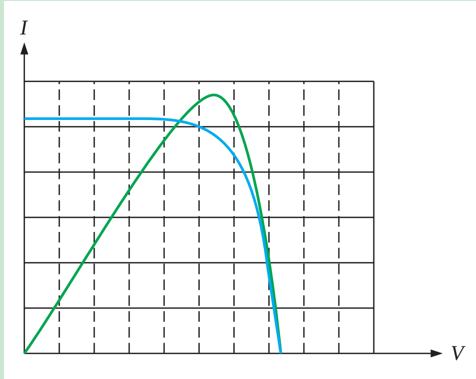
Basic concept of a PWM charge controller.

As you have learned, the output voltage of a solar panel varies greatly with the amount of sunlight and with the air temperature. For this reason, solar panels with voltage ratings higher than the battery voltage must be used in order to provide sufficient charging voltage to the battery under less than optimum conditions. As mentioned earlier, a 12 V solar panel may produce 20 V under optimum conditions but can produce only a certain amount of current. For example, if a solar panel can produce 8 A at 20 V, it is rated at 160 W. Batteries like to be charged at a voltage a little higher than their rated voltage. If a 12 V battery is being charged at 14 V, and it is drawing the maximum 8 A from the solar panel, the power delivered to the battery is 8 A $\times$ 14 V $=$ 112 W instead of the 160 W produced by the solar panel at 20 V. The batteries only stored 70% of the available energy because the 12 V battery cannot operate at 20 V.

MPPT (maximum power point tracker) charge controllers eliminate much of the energy loss found in the other types of controllers and produce much higher efficiencies. The MPPT continuously tracks the input voltage and current from the solar panel to determine when the peak input power occurs and then adjusts the voltage to the battery to optimize the charging. This results in a maximum power transfer from the solar panel to the battery. In Figure GA2–6, the blue curve is the voltage-current characteristic for a certain solar panel under a specified condition of incident light. The green curve is the power showing where the peak occurs, which is in the knee of the *V-I* curve. If the incident light decreases, the curves will shift down.

FIGURE GA2–6

Example of a solar panel *V-I* and power curves.



The MPPT is basically a DC-to-DC converter. A simplified block diagram showing the basic functional concept is shown in Figure GA2–7. Although there are several ways in which the MPPT can be implemented, the figure illustrates the basic functions. The DC/AC converter, the transformer, and the AC/DC converter isolate the dc input from the dc output, so the output can be adjusted for maximum power. For example, if a 160 W solar panel produces 20 V at 8 A, it needs to be reduced to approximately 13.6 V to charge a 12 V battery. A normal charger will not be able to provide more than 8 A at 13.6 V (or 109 W), which means the panel is not being used efficiently and only 76% of the available power from the solar panel is used. An MPPT charge controller can supply about 11 A at 13.6 V (150 W), thus decreasing the charging time and producing a better match between the panel and the battery. In this case, the panel is being used more efficiently because it is able to deliver about 94% of the available power to the battery.

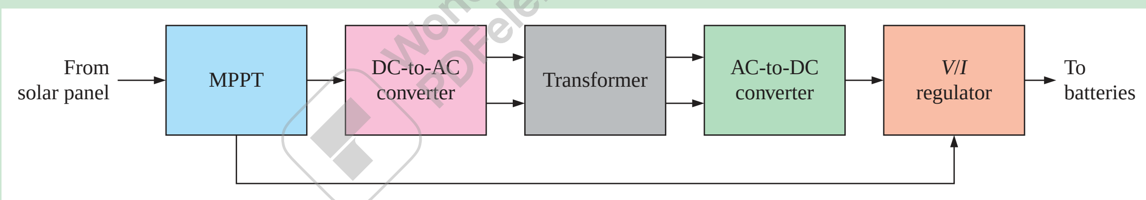


FIGURE GA2–7

Basic concept of an MPPT charge controller.

QUESTIONS

Some questions may require research beyond the content of this coverage. Answers can be found at www.pearsonhighered.com/floyd.

1. Why must deep-cycle batteries be used in solar power systems?
2. Why should a 12 V battery be charged at a higher than its rated voltage?
3. Which type of charge controller is the most efficient?
4. What range in terms of power is commercially available in charge controllers?
5. Two 12 V, 250 Ah batteries are connected in series and then connected in parallel with two more series-connected batteries of the same type. What is the total output voltage and Ah rating of the battery array?

The following websites are recommended for viewing charge controllers in action. Many other websites are also available.

http://www.youtube.com/watch?v=iifz1DxeaDQ

http://www.youtube.com/watch?v=P2XSbDRi6wo

http://www.youtube.com/watch?v=ITDh4aKXd80&feature=related

3 Special-Purpose Diodes

Chapter Outline

3–1 The Zener Diode
3–2 Zener Diode Applications
3–3 The Varactor Diode
3–4 Optical Diodes
3–5 Other Types of Diodes
3–6 Troubleshooting
Application Activity
Green Tech Application 3: *Solar Power*

Chapter Objectives

- Describe the characteristics of a zener diode and analyze its operation
- Apply a zener diode in voltage regulation
- Describe the varactor diode characteristic and analyze its operation
- Discuss the characteristics, operation, and applications of LEDs, quantum dots, and photodiodes
- Discuss the basic characteristics of several types of diodes
- Troubleshoot zener diode regulators

Key Terms

- Zener diode
- Zener breakdown
- Varactor
- Light-emitting diode (LED)
- Electroluminescence
- Pixel
- Photodiode
- Laser

Visit the Companion Website

Study aids and Multisim files for this chapter are available at http://www.pearsonhighered.com/electronics

Introduction

Chapter 2 was devoted to general-purpose and rectifier diodes, which are the most widely used types. In this chapter, we will cover several other types of diodes that are designed for specific applications, including the zener, varactor (variable-capacitance), light-emitting, photo, laser, Schottky, tunnel, *pin*, step-recovery, and current regulator diodes.

Application Activity Preview

The Application Activity in this chapter is the expansion of the 16 V power supply developed in Chapter 2 into a 12 V regulated power supply with an LED power-on indicator. The new circuit will incorporate a voltage regulator IC, which is introduced in this chapter.

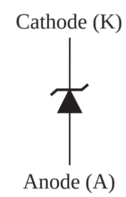
3–1 THE ZENER DIODE

A major application for zener diodes is as a type of voltage regulator for providing stable reference voltages for use in power supplies, voltmeters, and other instruments. In this section, you will see how the zener diode maintains a nearly constant dc voltage under the proper operating conditions. You will learn the conditions and limitations for properly using the zener diode and the factors that affect its performance.

After completing this section, you should be able to

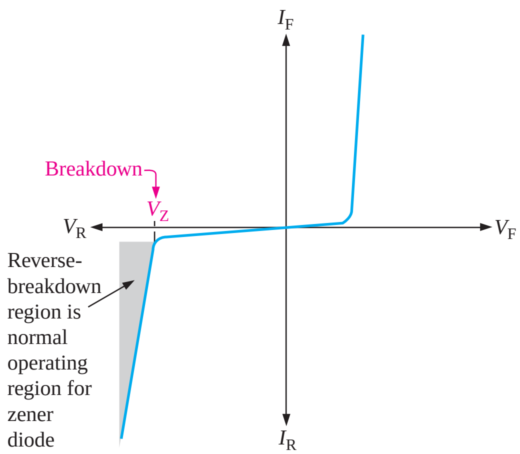
- **Describe the characteristics of a zener diode and analyze its operation**
- Recognize a zener diode by its schematic symbol
- Discuss zener breakdown
  - Define *avalanche breakdown*
- Explain zener breakdown characteristics
  - Describe zener regulation
- Discuss zener equivalent circuits
- Define *temperature coefficient*
  - Analyze zener voltage as a function of temperature
- Discuss zener power dissipation and derating
  - Apply power derating to a zener diode
- Interpret zener diode datasheets

The symbol for a zener diode is shown in Figure 3–1. Instead of a straight line representing the cathode, the zener diode has a bent line that reminds you of the letter Z (for zener). A **zener diode** is a silicon *pn* junction device that is designed for operation in the reverse-breakdown region. The breakdown voltage of a zener diode is set by carefully controlling the doping level during manufacture. Recall, from the discussion of the diode characteristic curve in Chapter 2, that when a diode reaches reverse breakdown, its voltage remains almost constant even though the current changes drastically, and this is the key to zener diode operation. This volt-ampere characteristic is shown again in Figure 3–2 with the normal operating region for zener diodes shown as a shaded area.



▲ FIGURE 3–1

Zener diode symbol.



◀ FIGURE 3–2

General zener diode *V-I* characteristic.

Zener Breakdown

Zener diodes are designed to operate in reverse breakdown. Two types of reverse breakdown in a zener diode are *avalanche* and *zener.* The avalanche effect, discussed in Chapter 2, occurs in both rectifier and zener diodes at a sufficiently high reverse voltage. **Zener breakdown**

HISTORY NOTE

Clarence Melvin Zener, an American physicist, was born in Indianapolis and earned his PhD from Harvard in 1930. He was the first to describe the properties of reverse breakdown that are exploited by the zener diode. As a result, Bell Labs, where the device was developed, named the diode after him. He was also involved in areas of superconductivity, metallurgy, and geometric programming.

occurs in a zener diode at low reverse voltages. A zener diode is heavily doped to reduce the breakdown voltage. This causes a very thin depletion region. As a result, an intense electric field exists within the depletion region. Near the zener breakdown voltage (V_Z), the field is intense enough to pull electrons from their valence bands and create current.

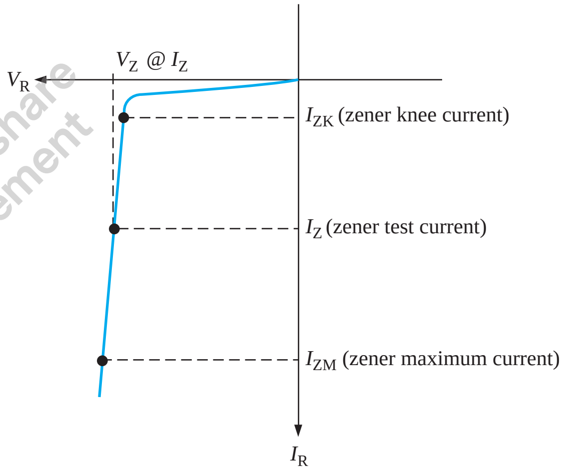
Zener diodes with breakdown voltages of less than approximately 5 V operate predominately in zener breakdown. Those with breakdown voltages greater than approximately 5 V operate predominately in **avalanche breakdown.** Both types, however, are called *zener diodes.* Zeners are commercially available with breakdown voltages from less than 1 V to more than 250 V with specified tolerances from 1% to 20%.

Breakdown Characteristics

Figure 3–3 shows the reverse portion of a zener diode's characteristic curve. Notice that as the reverse voltage (V_R) is increased, the reverse current (I_R) remains extremely small up to the "knee" of the curve. The reverse current is also called the zener current, I_Z. At this point, the breakdown effect begins; the internal zener resistance, also called zener impedance (Z_Z), begins to decrease as the reverse current increases rapidly. From the bottom of the knee, the zener breakdown voltage (V_Z) remains essentially constant although it increases slightly as the zener current, I_Z, increases.

FIGURE 3–3

Reverse characteristic of a zener diode. V_Z is usually specified at a value of the zener current known as the test current.

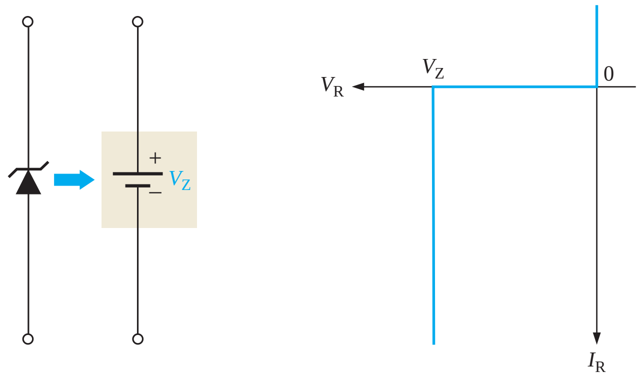


Zener Regulation The ability to keep the reverse voltage across its terminals essentially constant is the key feature of the zener diode. A zener diode operating in breakdown acts as a voltage regulator because it maintains a nearly constant voltage across its terminals over a specified range of reverse-current values.

A minimum value of reverse current, I_{ZK}, must be maintained in order to keep the diode in breakdown for voltage regulation. You can see on the curve in Figure 3–3 that when the reverse current is reduced below the knee of the curve, the voltage decreases drastically and regulation is lost. Also, there is a maximum current, I_{ZM}, above which the diode may be damaged due to excessive power dissipation. So, basically, the zener diode maintains a nearly constant voltage across its terminals for values of reverse current ranging from I_{ZK} to I_{ZM}. A nominal zener voltage, V_Z, is usually specified on a datasheet at a value of reverse current called the *zener test current.*

Zener Equivalent Circuits

Figure 3–4 shows the ideal model (first approximation) of a zener diode in reverse breakdown and its ideal characteristic curve. It has a constant voltage drop equal to the nominal zener voltage. This constant voltage drop across the zener diode produced by reverse breakdown is represented by a dc voltage symbol even though the zener diode does not produce a voltage.



(a) Ideal model (b) Ideal characteristic curve

FIGURE 3–4

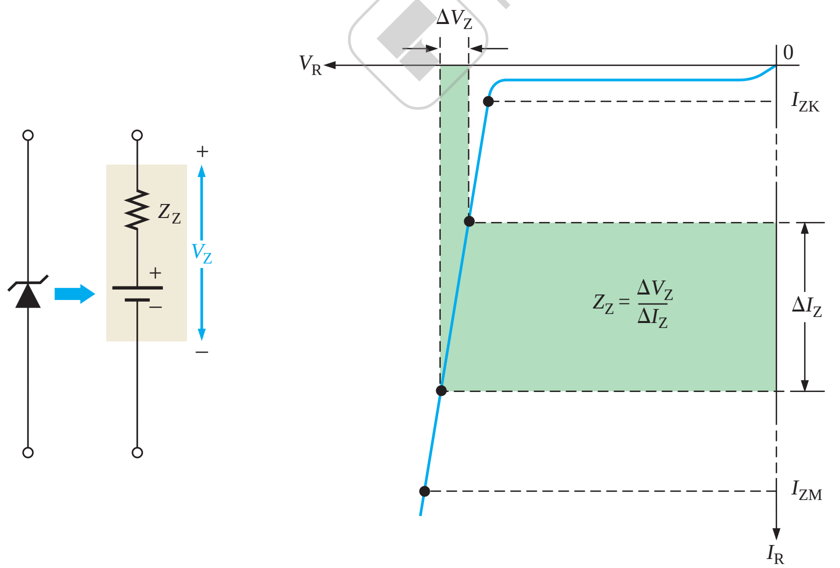
Ideal zener diode equivalent circuit model and the characteristic curve.

Figure 3–5(a) represents the practical model (second approximation) of a zener diode, where the zener impedance (resistance), Z_Z, is included. Since the actual voltage curve is not ideally vertical, a change in zener current (ΔI_Z) produces a small change in zener voltage (ΔV_Z), as illustrated in Figure 3–5(b). By Ohm's law, the ratio of ΔV_Z to ΔI_Z is the impedance, as expressed in the following equation:

$$Z_Z = \frac{\Delta V_Z}{\Delta I_Z}$$

Equation 3–1

Normally, Z_Z is specified at the zener test current. In most cases, you can assume that Z_Z is a small constant over the full range of zener current values and is purely resistive. It is best to avoid operating a zener diode near the knee of the curve because the impedance changes dramatically in that area.



(a) Practical model (b) Characteristic curve. The slope is exaggerated for illustration.

FIGURE 3–5

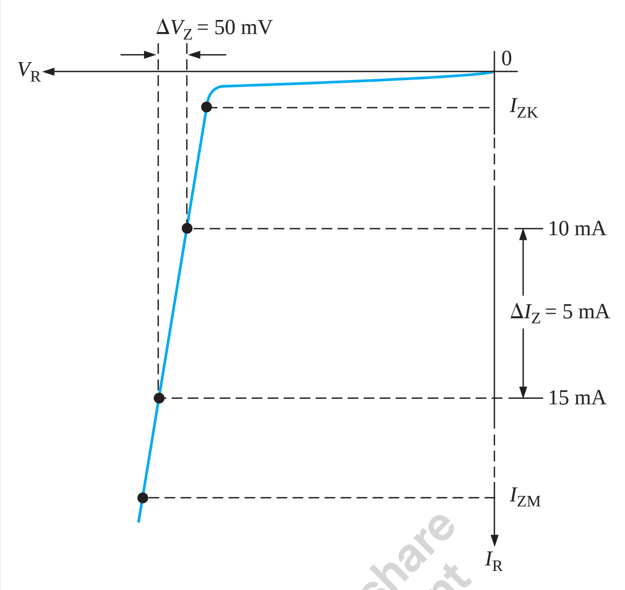
Practical zener diode equivalent circuit and the characteristic curve illustrating Z_Z.

For most circuit analysis and troubleshooting work, the ideal model will give very good results and is much easier to use than more complicated models. When a zener diode is operating normally, it will be in reverse breakdown and you should observe the nominal breakdown voltage across it. Most **schematics** will indicate on the drawing what this voltage should be.

EXAMPLE 3–1

A zener diode exhibits a certain change in V_Z for a certain change in I_Z on a portion of the linear characteristic curve between I_{ZK} and I_{ZM} as illustrated in Figure 3–6. What is the zener impedance?

▶ FIGURE 3–6



Solution

$$Z_Z = \frac{\Delta V_Z}{\Delta I_Z} = \frac{50\text{ mV}}{5\text{ mA}} = \mathbf{10\ \Omega}$$

*Related Problem** Calculate the zener impedance if the change in zener voltage is 100 mV for a 20 mA change in zener current on the linear portion of the characteristic curve.

*Answers can be found at www.pearsonhighered.com/floyd.

Temperature Coefficient

The temperature coefficient specifies the percent change in zener voltage for each degree Celsius change in temperature. For example, a 12 V zener diode with a positive temperature coefficient of 0.01%/°C will exhibit a 1.2 mV increase in V_Z when the junction temperature increases one degree Celsius. The formula for calculating the change in zener voltage for a given junction temperature change, for a specified temperature coefficient, is

Equation 3–2

$$\Delta V_Z = V_Z \times TC \times \Delta T$$

where V_Z is the nominal zener voltage at the reference temperature of 25°C, TC is the temperature coefficient, and ΔT is the change in temperature from the reference temperature. A positive TC means that the zener voltage increases with an increase in temperature or decreases with a decrease in temperature. A negative TC means that the zener voltage decreases with an increase in temperature or increases with a decrease in temperature.

In some cases, the temperature coefficient is expressed in mV/°C rather than as %/°C. For these cases, ΔV_Z is calculated as

Equation 3–3

$$\Delta V_Z = TC \times \Delta T$$

EXAMPLE 3–2

An 8.2 V zener diode (8.2 V at 25°C) has a positive temperature coefficient of 0.05%/°C. What is the zener voltage at 60°C?

Solution The change in zener voltage is

$$\Delta V_Z = V_Z \times TC \times \Delta T = (8.2\text{ V})(0.05\%/°\text{C})(60°\text{C} - 25°\text{C})$$
$$= (8.2\text{ V})(0.0005/°\text{C})(35°\text{C}) = 144\text{ mV}$$

Notice that 0.05%/°C was converted to 0.0005/°C. The zener voltage at 60°C is

$$V_Z + \Delta V_Z = 8.2\text{ V} + 144\text{ mV} = \mathbf{8.34\text{ V}}$$

Related Problem A 12 V zener has a positive temperature coefficient of 0.075%/°C. How much will the zener voltage change when the junction temperature decreases 50 degrees Celsius?

Zener Power Dissipation and Derating

Zener diodes are specified to operate at a maximum power called the maximum dc power dissipation, $P_{D(max)}$. For example, the 1N746 zener is rated at a $P_{D(max)}$ of 500 mW and the 1N3305A is rated at a $P_{D(max)}$ of 50 W. The dc power dissipation is determined by the formula,

$$P_D = V_Z I_Z$$

Power Derating The maximum power dissipation of a zener diode is typically specified for temperatures at or below a certain value (50°C, for example). Above the specified temperature, the maximum power dissipation is reduced according to a derating factor. The derating factor is expressed in mW/°C. The maximum derated power can be determined with the following formula:

$$P_{D(derated)} = P_{D(max)} - (\text{mW}/°\text{C})\Delta T$$

EXAMPLE 3–3

A certain zener diode has a maximum power rating of 400 mW at 50°C and a derating factor of 3.2 mW/°C. Determine the maximum power the zener can dissipate at a temperature of 90°C.

Solution

$$P_{D(derated)} = P_{D(max)} - (\text{mW}/°\text{C})\Delta T$$
$$= 400\text{ mW} - (3.2\text{ mW}/°\text{C})(90°\text{C} - 50°\text{C})$$
$$= 400\text{ mW} - 128\text{ mW} = \mathbf{272\text{ mW}}$$

Related Problem A certain 50 W zener diode must be derated with a derating factor of 0.5 W/°C above 75°C. Determine the maximum power it can dissipate at 160°C.

Zener Diode Datasheet Information

The amount and type of information found on datasheets for zener diodes (or any category of electronic device) varies from one type of diode to the next. The datasheet for some zeners contains more information than for others. Figure 3–7 gives an example of the type of information you have studied that can be found on a typical datasheet. This particular information is for a zener series, the 1N4728A–1N4764A.

FAIRCHILD SEMICONDUCTOR®

1N4728A - 1N4764A

Zeners

DO-41 Glass case

COLOR BAND DENOTES CATHODE

Absolute Maximum Ratings * T_a = 25°C unless otherwise noted

Symbol	Parameter	Value	Units
P_D	Power Dissipation @ TL ≤ 50°C, Lead Length = 3/8"	1.0	W
	Derate above 50°C	6.67	mW/°C
T_J, T_{STG}	Operating and Storage Temperature Range	-65 to +200	°C

* These ratings are limiting values above which the serviceability of the diode may be impaired.

Electrical Characteristics T_a = 25°C unless otherwise noted

Device	V_Z (V) @ I_Z (Note 1)			Test Current	Max. Zener Impedance			Leakage Current	
	Min.	Typ.	Max.	I_Z (mA)	Z_Z @ I_Z (Ω)	Z_{ZK} @ I_{ZK} (Ω)	I_{ZK} (mA)	I_R (μA)	V_R (V)
1N4728A	3.315	3.3	3.465	76	10	400	1	100	1
1N4729A	3.42	3.6	3.78	69	10	400	1	100	1
1N4730A	3.705	3.9	4.095	64	9	400	1	50	1
1N4731A	4.085	4.3	4.515	58	9	400	1	10	1
1N4732A	4.465	4.7	4.935	53	8	500	1	10	1
1N4733A	4.845	5.1	5.355	49	7	550	1	10	1
1N4734A	5.32	5.6	5.88	45	5	600	1	10	2
1N4735A	5.89	6.2	6.51	41	2	700	1	10	3
1N4736A	6.46	6.8	7.14	37	3.5	700	1	10	4
1N4737A	7.125	7.5	7.875	34	4	700	0.5	10	5
1N4738A	7.79	8.2	8.61	31	4.5	700	0.5	10	6
1N4739A	8.645	9.1	9.555	28	5	700	0.5	10	7
1N4740A	9.5	10	10.5	25	7	700	0.25	10	7.6
1N4741A	10.45	11	11.55	23	8	700	0.25	5	8.4
1N4742A	11.4	12	12.6	21	9	700	0.25	5	9.1
1N4743A	12.35	13	13.65	19	10	700	0.25	5	9.9
1N4744A	14.25	15	15.75	17	14	700	0.25	5	11.4
1N4745A	15.2	16	16.8	15.5	16	700	0.25	5	12.2
1N4746A	17.1	18	18.9	14	20	750	0.25	5	13.7
1N4747A	19	20	21	12.5	22	750	0.25	5	15.2
1N4748A	20.9	22	23.1	11.5	23	750	0.25	5	16.7
1N4749A	22.8	24	25.2	10.5	25	750	0.25	5	18.2
1N4750A	25.65	27	28.35	9.5	35	750	0.25	5	20.6
1N4751A	28.5	30	31.5	8.5	40	1000	0.25	5	22.8
1N4752A	31.35	33	34.65	7.5	45	1000	0.25	5	25.1
1N4753A	34.2	36	37.8	7	50	1000	0.25	5	27.4
1N4754A	37.05	39	40.95	6.5	60	1000	0.25	5	29.7
1N4755A	40.85	43	45.15	6	70	1500	0.25	5	32.7
1N4756A	44.65	47	49.35	5.5	80	1500	0.25	5	35.8
1N4757A	48.45	51	53.55	5	95	1500	0.25	5	38.8
1N4758A	53.2	56	58.8	4.5	110	2000	0.25	5	42.6
1N4759A	58.9	62	65.1	4	125	2000	0.25	5	47.1
1N4760A	64.6	68	71.4	3.7	150	2000	0.25	5	51.7
1N4761A	71.25	75	78.75	3.3	175	2000	0.25	5	56
1N4762A	77.9	82	86.1	3	200	3000	0.25	5	62.2
1N4763A	86.45	91	95.55	2.8	250	3000	0.25	5	69.2
1N4764A	95	100	105	2.5	350	3000	0.25	5	76

Notes:

1. Zener Voltage (V_Z)
The zener voltage is measured with the device junction in the thermal equilibrium at the lead temperature (T_L) at 30°C ± 1°C and 3/8" lead length.

▲ **FIGURE 3–7**

Partial datasheet for the 1N4728A–1N4764A series 1 W zener diodes. Copyright Fairchild Semiconductor Corporation. Used by permission. Datasheets are available at www.fairchildsemi.com.

Absolute Maximum Ratings The maximum power dissipation, P_D, is specified as 1.0 W up to 50°C. Generally, the zener diode should be operated at least 20% below this maximum to assure reliability and longer life. The power dissipation is derated as shown on the datasheet at 6.67 mW for each degree above 50°C. For example, using the procedure illustrated in Example 3–3, the maximum power dissipation at 60°C is

$$P_D = 1\text{ W} - 10°\text{C}(6.67\text{ mW/°C}) = 1\text{ W} - 66.7\text{ mW} = 0.9933\text{ W}$$

At 125°C, the maximum power dissipation is

$$P_D = 1\text{ W} - 75°\text{C}(6.67\text{ mW/°C}) = 1\text{ W} - 500.25\text{ mW} = 0.4998\text{ W}$$

Notice that a maximum reverse current is not specified but can be determined from the maximum power dissipation for a given value of V_Z. For example, at 50°C, the maximum zener current for a zener voltage of 3.3 V is

$$I_{ZM} = \frac{P_D}{V_Z} = \frac{1\text{ W}}{3.3\text{ V}} = 303\text{ mA}$$

The operating junction temperature, T_J, and the storage temperature, T_{STG}, have a range of from −65°C to 200°C.

Electrical Characteristics The first column in the datasheet lists the zener type numbers, 1N4728A through 1N4764A.

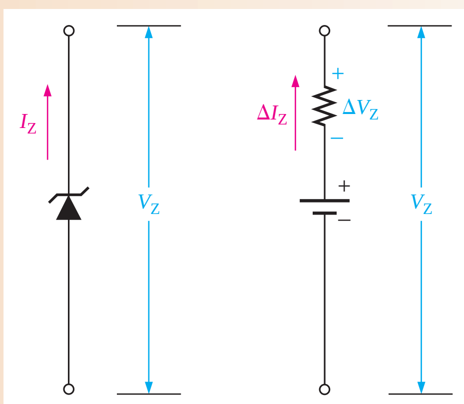
Zener voltage, V_Z, and zener test current, I_Z For each device type, the minimum, typical, and maximum zener voltages are listed. V_Z is measured at the specified zener test current, I_Z. For example, the zener voltage for a 1N4728A can range from 3.315 V to 3.465 V with a typical value of 3.3 V at a test current of 76 mA.

Maximum zener impedance Z_Z is the maximum zener impedance at the specified test current, I_Z. For example, for a 1N4728A, Z_Z is 10 Ω at 76 mA. The maximum zener impedance, Z_{ZK}, at the knee of the characteristic curve is specified at I_{ZK}, which is the current at the knee of the curve. For example, Z_{ZK} is 400 Ω at 1 mA for a 1N4728A.

Leakage current Reverse leakage current is specified for a reverse voltage that is less than the knee voltage. This means that the zener is not in reverse breakdown for these measurements. For example I_R is 100 μA for a reverse voltage of 1 V in a 1N4728A.

EXAMPLE 3–4

From the datasheet in Figure 3–7, a 1N4736A zener diode has a Z_Z of 3.5 Ω. The datasheet gives $V_Z = 6.8$ V at a test current, I_Z, of 37 mA. What is the voltage across the zener terminals when the current is 50 mA? When the current is 25 mA? Figure 3–8 represents the zener diode.



▲ FIGURE 3–8

Solution For $I_Z = 50$ mA: The 50 mA current is a 13 mA increase above the test current, I_Z, of 37 mA.

$$\Delta I_Z = I_Z - 37\text{ mA} = 50\text{ mA} - 37\text{ mA} = +13\text{ mA}$$
$$\Delta V_Z = \Delta I_Z Z_Z = (13\text{ mA})(3.5\ \Omega) = +45.5\text{ mV}$$

The change in voltage due to the increase in current above the I_Z value causes the zener terminal voltage to increase. The zener voltage for $I_Z = 50$ mA is

$$V_Z = 6.8\text{ V} + \Delta V_Z = 6.8\text{ V} + 45.5\text{ mV} = \mathbf{6.85\text{ V}}$$

For $I_Z = 25$ mA: The 25 mA current is a 12 mA decrease below the test current, I_Z, of 37 mA.

$$\Delta I_Z = -12\text{ mA}$$
$$\Delta V_Z = \Delta I_Z Z_Z = (-12\text{ mA})(3.5\ \Omega) = -42\text{ mV}$$

The change in voltage due to the decrease in current below the test current causes the zener terminal voltage to decrease. The zener voltage for $I_Z = 25$ mA is

$$V_Z = 6.8\text{ V} - \Delta V_Z = 6.8\text{ V} - 42\text{ mV} = \mathbf{6.76\text{ V}}$$

Related Problem Repeat the analysis for $I_Z = 10$ mA and for $I_Z = 30$ mA using a 1N4742A zener with $V_Z = 12$ V at $I_Z = 21$ mA and $Z_Z = 9\ \Omega$.

SECTION 3–1 CHECKUP
Answers can be found at www.pearsonhighered.com/floyd.

1. In what region of their characteristic curve are zener diodes operated?
2. At what value of zener current is the zener voltage normally specified?
3. How does the zener impedance affect the voltage across the terminals of the device?
4. What does a positive temperature coefficient of **0.05%/°C** mean?
5. Explain power derating.

3–2 ZENER DIODE APPLICATIONS

The zener diode can be used as a type of voltage regulator for providing stable reference voltages. In this section, you will see how zeners can be used as voltage references, regulators, and as simple limiters or clippers.

After completing this section, you should be able to

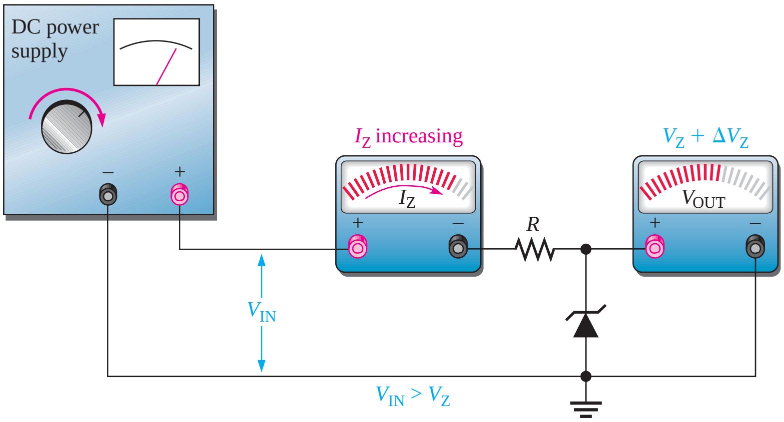
- **Apply a zener diode in voltage regulation**
- Analyze zener regulation with a variable input voltage
- Discuss zener regulation with a variable load
- Describe zener regulation from no load to full load
- Discuss zener limiting

Zener Regulation with a Variable Input Voltage

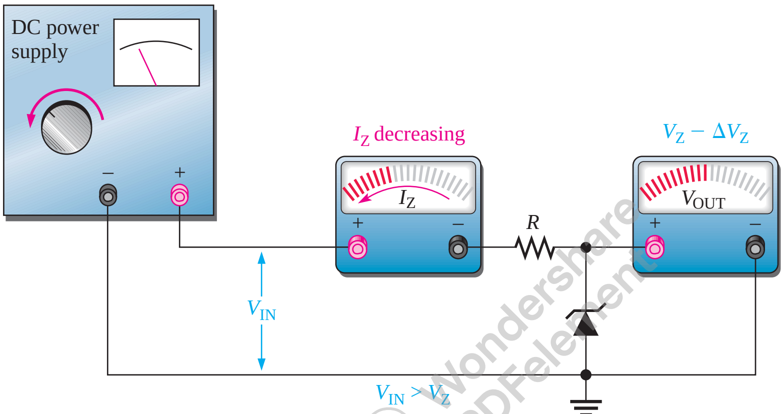
Zener diode regulators can provide a reasonably constant dc level at the output, but they are not particularly efficient. For this reason, they are limited to applications that require only low current to the load. Figure 3–9 illustrates how a zener diode can be used to regulate a dc

FIGURE 3–9

Zener regulation of a varying input voltage.



(a) As the input voltage increases, the output voltage remains nearly constant ($I_{ZK} < I_Z < I_{ZM}$).



(b) As the input voltage decreases, the output voltage remains nearly constant ($I_{ZK} < I_Z < I_{ZM}$).

voltage. As the input voltage varies (within limits), the zener diode maintains a nearly constant output voltage across its terminals. However, as V_{IN} changes, I_Z will change proportionally so that the limitations on the input voltage variation are set by the minimum and maximum current values (I_{ZK} and I_{ZM}) with which the zener can operate. Resistor R is the series current-limiting resistor. The meters indicate the relative values and trends.

To illustrate regulation, let's use the ideal model of the 1N4740A zener diode (ignoring the zener resistance) in the circuit of Figure 3–10. The absolute lowest current that will maintain regulation is specified at I_{ZK}, which for the 1N4740A is 0.25 mA and represents the no-load current. The maximum current is not given on the datasheet but can be calculated from the power specification of 1 W, which is given on the datasheet. Keep in mind that both the minimum and maximum values are at the operating extremes and represent worst-case operation.

$$I_{ZM} = \frac{P_{D(max)}}{V_Z} = \frac{1\text{ W}}{10\text{ V}} = 100\text{ mA}$$

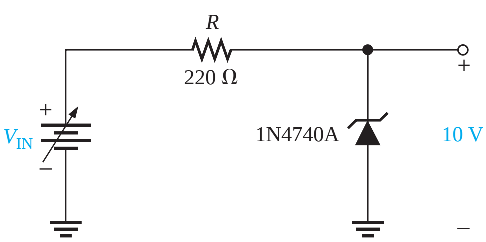


FIGURE 3–10

For the minimum zener current, the voltage across the 220 Ω resistor is

$$V_R = I_{ZK}R = (0.25\text{ mA})(220\ \Omega) = 55\text{ mV}$$

Since $V_R = V_{IN} - V_Z$,

$$V_{IN(min)} = V_R + V_Z = 55\text{ mV} + 10\text{ V} = 10.055\text{ V}$$

For the maximum zener current, the voltage across the 220 Ω resistor is

$$V_R = I_{ZM}R = (100\text{ mA})(220\ \Omega) = 22\text{ V}$$

Therefore,

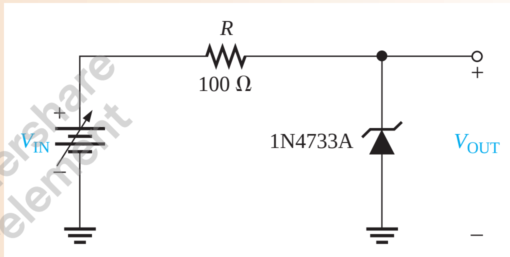
$$V_{IN(max)} = 22\text{ V} + 10\text{ V} = 32\text{ V}$$

This shows that this zener diode can ideally regulate an input voltage from 10.055 V to 32 V and maintain an approximate 10 V output. The output will vary slightly because of the zener impedance, which has been neglected in these calculations.

EXAMPLE 3–5

Determine the minimum and the maximum input voltages that can be regulated by the zener diode in Figure 3–11.

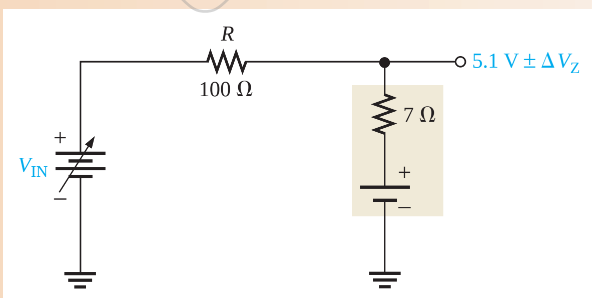
▶ **FIGURE 3–11**



Solution From the datasheet in Figure 3–7 for the 1N4733A: $V_Z = 5.1$ V at $I_Z = 49$ mA, $I_{ZK} = 1$ mA, and $Z_Z = 7\ \Omega$ at I_Z. For simplicity, assume this value of Z_Z over the range of current values. The equivalent circuit is shown in Figure 3–12.

▶ **FIGURE 3–12**

Equivalent of circuit in Figure 3–11.



At $I_{ZK} = 1$ mA, the output voltage is

$$V_{OUT} \cong 5.1\text{ V} - \Delta V_Z = 5.1\text{ V} - (I_Z - I_{ZK})Z_Z = 5.1\text{ V} - (49\text{ mA} - 1\text{ mA})(7\ \Omega)$$
$$= 5.1\text{ V} - (48\text{ mA})(7\ \Omega) = 5.1\text{ V} - 0.336\text{ V} = 4.76\text{ V}$$

Therefore,

$$V_{IN(min)} = I_{ZK}R + V_{OUT} = (1\text{ mA})(100\ \Omega) + 4.76\text{ V} = \mathbf{4.86\text{ V}}$$

To find the maximum input voltage, first calculate the maximum zener current. Assume the temperature is 50°C or below; so from Figure 3–7, the power dissipation is 1 W.

$$I_{ZM} = \frac{P_{D(max)}}{V_Z} = \frac{1\text{ W}}{5.1\text{ V}} = 196\text{ mA}$$

At I_{ZM}, the output voltage is

$$V_{OUT} \cong 5.1\text{ V} + \Delta V_Z = 5.1\text{ V} + (I_{ZM} - I_Z)Z_Z$$
$$= 5.1\text{ V} + (147\text{ mA})(7\ \Omega) = 5.1\text{ V} + 1.03\text{ V} = 6.13\text{ V}$$

Therefore,

$$V_{IN(max)} = I_{ZM}R + V_{OUT} = (196\text{ mA})(100\ \Omega) + 6.13\text{ V} = \mathbf{25.7\ V}$$

Related Problem Determine the minimum and maximum input voltages that can be regulated if a 1N4736A zener diode is used in Figure 3–11.

Open the Multisim file E03-05 in the Examples folder on the companion website. For the calculated minimum and maximum dc input voltages, measure the resulting output voltages. Compare with the calculated values.

Zener Regulation with a Variable Load

Figure 3–13 shows a zener voltage regulator with a variable load resistor across the terminals. The zener diode maintains a nearly constant voltage across R_L as long as the zener current is greater than I_{ZK} and less than I_{ZM}.

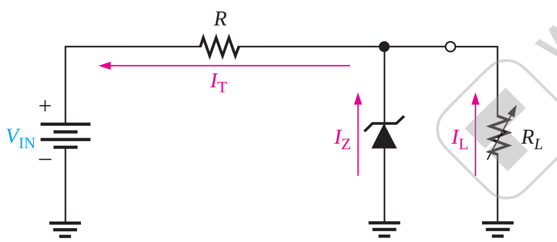


FIGURE 3–13

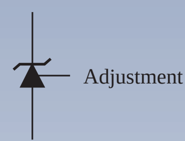
Zener regulation with a variable load.

From No Load to Full Load

When the output terminals of the zener regulator are open ($R_L = \infty$), the load current is zero and *all* of the current is through the zener; this is a no-load condition. When a load resistor (R_L) is connected, part of the total current is through the zener and part through R_L. The total current through R remains essentially constant as long as the zener is regulating. As R_L is decreased, the load current, I_L, increases and I_Z decreases. The zener diode continues to regulate the voltage until I_Z reaches its minimum value, I_{ZK}. At this point the load current is maximum, and a full-load condition exists. The following example will illustrate this.

FYI

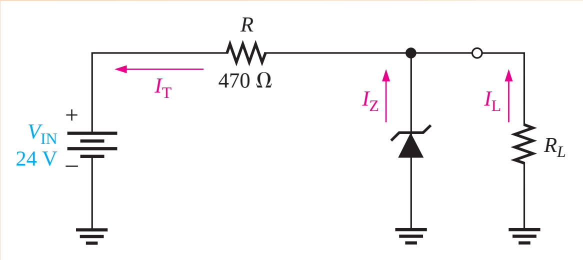
One type of temperature sensor uses the zener diode breakdown voltage as a temperature indicator. The breakdown voltage of a zener is directly proportional to the Kelvin temperature. This type of sensor is small, accurate, and linear. The LM125/LM235/LM335 is an integrated circuit that is more complex than a simple zener diode. However, it displays a very precise zener characteristic. In addition to the anode and cathode terminals, this device has an adjustment for calibration purposes. The symbol is shown below.



EXAMPLE 3–6

Determine the minimum and the maximum load currents for which the zener diode in Figure 3–14 will maintain regulation. What is the minimum value of R_L that can be used? $V_Z = 12$ V, $I_{ZK} = 1$ mA, and $I_{ZM} = 50$ mA. Assume an ideal zener diode where $Z_Z = 0\ \Omega$ and V_Z remains a constant 12 V over the range of current values, for simplicity.

▶ **FIGURE 3–14**



Solution When $I_L = 0$ A ($R_L = \infty$), I_Z is maximum and equal to the total circuit current I_T.

$$I_{Z(max)} = I_T = \frac{V_{IN} - V_Z}{R} = \frac{24\text{ V} - 12\text{ V}}{470\ \Omega} = 25.5\text{ mA}$$

If R_L is removed from the circuit, the load current is 0 A. Since $I_{Z(max)}$ is less than I_{ZM}, 0 A is an acceptable minimum value for I_L because the zener can handle all of the 25.5 mA.

$$I_{L(min)} = \mathbf{0\ A}$$

The maximum value of I_L occurs when I_Z is minimum ($I_Z = I_{ZK}$), so

$$I_{L(max)} = I_T - I_{ZK} = 25.5\text{ mA} - 1\text{ mA} = \mathbf{24.5\ mA}$$

The minimum value of R_L is

$$R_{L(min)} = \frac{V_Z}{I_{L(max)}} = \frac{12\text{ V}}{24.5\text{ mA}} = \mathbf{490\ \Omega}$$

Therefore, if R_L is less than 490 Ω, R_L will draw more of the total current away from the zener and I_Z will be reduced below I_{ZK}. This will cause the zener to lose regulation. Regulation is maintained for any value of R_L between 490 Ω and infinity.

Related Problem Find the minimum and maximum load currents for which the circuit in Figure 3–14 will maintain regulation. Determine the minimum value of R_L that can be used. $V_Z = 3.3$ V (constant), $I_{ZK} = 1$ mA, and $I_{ZM} = 150$ mA. Assume an ideal zener.

Open the Multisim file E03-06 in the Examples folder on the companion website. For the calculated minimum value of load resistance, verify that regulation occurs.

In the last example, we assumed that Z_Z was zero and, therefore, the zener voltage remained constant over the range of currents. We made this assumption to demonstrate the concept of how the regulator works with a varying load. Such an assumption is often acceptable and in many cases produces results that are reasonably accurate. In Example 3–7, we will take the zener impedance into account.

EXAMPLE 3–7

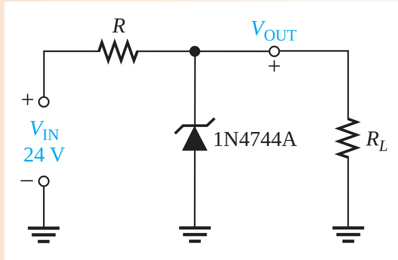
For the circuit in Figure 3–15:

(a) Determine V_{OUT} at I_{ZK} and at I_{ZM}.

(b) Calculate the value of R that should be used.

(c) Determine the minimum value of R_L that can be used.

▶ **FIGURE 3–15**



Solution The 1N4744A zener used in the regulator circuit of Figure 3–15 is a 15 V diode. The datasheet in Figure 3–7 gives the following information:
$V_Z = 15\text{ V} @ I_Z = 17\text{ mA}$, $I_{ZK} = 0.25\text{ mA}$, and $Z_Z = 14\ \Omega$.

(a) For I_{ZK}:

$$V_{OUT} = V_Z - \Delta I_Z Z_Z = 15\text{ V} - \Delta I_Z Z_Z = 15\text{ V} - (I_Z - I_{ZK})Z_Z$$
$$= 15\text{ V} - (16.75\text{ mA})(14\ \Omega) = 15\text{ V} - 0.235\text{ V} = \mathbf{14.76\ V}$$

Calculate the zener maximum current. The maximum power dissipation is 1 W.

$$I_{ZM} = \frac{P_{D(max)}}{V_Z} = \frac{1\text{ W}}{15\text{ V}} = 66.7\text{ mA}$$

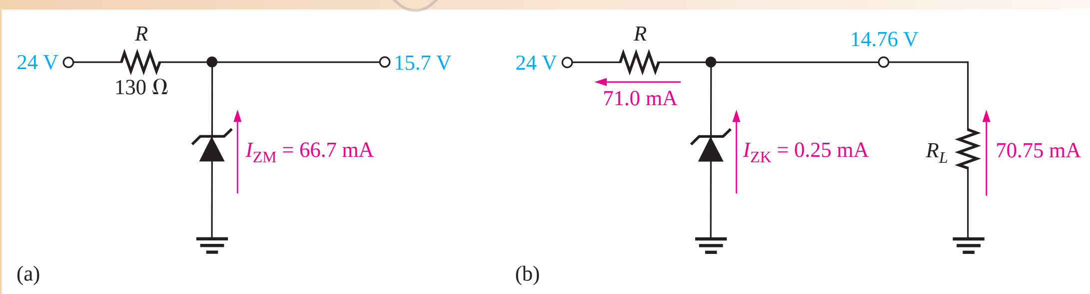
For I_{ZM}:

$$V_{OUT} = V_Z + \Delta I_Z Z_Z = 15\text{ V} + \Delta I_Z Z_Z$$
$$= 15\text{ V} + (I_{ZM} - I_Z)Z_Z = 15\text{ V} + (49.7\text{ mA})(14\ \Omega) = \mathbf{15.7\ V}$$

(b) Calculate the value of R for the maximum zener current that occurs when there is no load as shown in Figure 3–16(a).

$$R = \frac{V_{IN} - V_{OUT}}{I_{ZK}} = \frac{24\text{ V} - 15.7\text{ V}}{66.7\text{ mA}} = 124\ \Omega$$

$R = \mathbf{130\ \Omega}$ (nearest larger standard value).



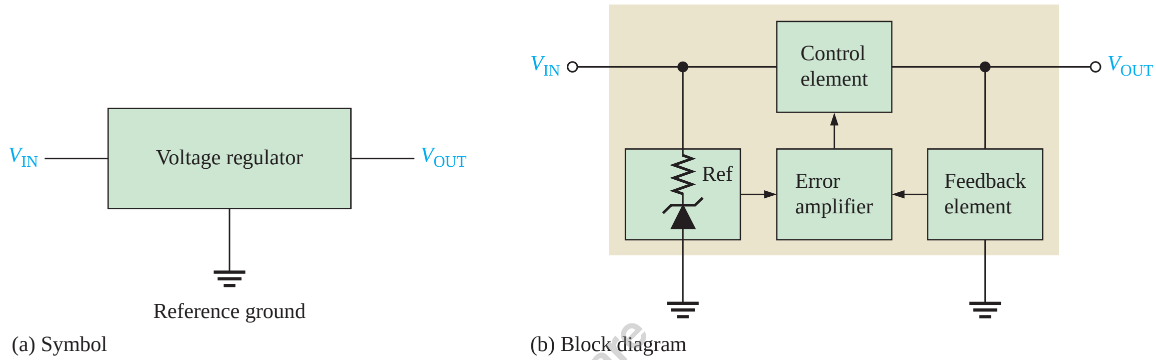
▲ **FIGURE 3–16**

(c) For the minimum load resistance (maximum load current), the zener current is minimum ($I_{ZK} = 0.25\text{ mA}$) as shown in Figure 3–16(b).

$$I_T = \frac{V_{IN} - V_{OUT}}{R} = \frac{24\text{ V} - 14.76\text{ V}}{130\ \Omega} = 71.0\text{ mA}$$
$$I_L = I_T - I_{ZK} = 71.0\text{ mA} - 0.25\text{ mA} = 70.75\text{ mA}$$
$$R_{L(min)} = \frac{V_{OUT}}{I_L} = \frac{14.76\text{ V}}{70.75\text{ mA}} = \mathbf{209\ \Omega}$$

Related Problem Repeat each part of the preceding analysis if the zener is changed to a 1N4742A 12 V device.

You have seen how the zener diode regulates voltage. Its regulating ability is somewhat limited by the change in zener voltage over a range of current values, which restricts the load current that it can handle. To achieve better regulation and provide for greater variations in load current, the zener diode is combined as a key element with other circuit components to create a 3-terminal linear voltage regulator. Three-terminal voltage regulators that were introduced in Chapter 2 are IC devices that use the zener to provide a reference voltage for an internal amplifier. For a given dc input voltage, the 3-terminal regulator maintains an essentially constant dc voltage over a range of input voltages and load currents. The dc output voltage is always less than the input voltage. The details of this type of regulator are covered in Chapter 17. Figure 3–17 illustrates a basic 3-terminal regulator showing where the zener diode is used.

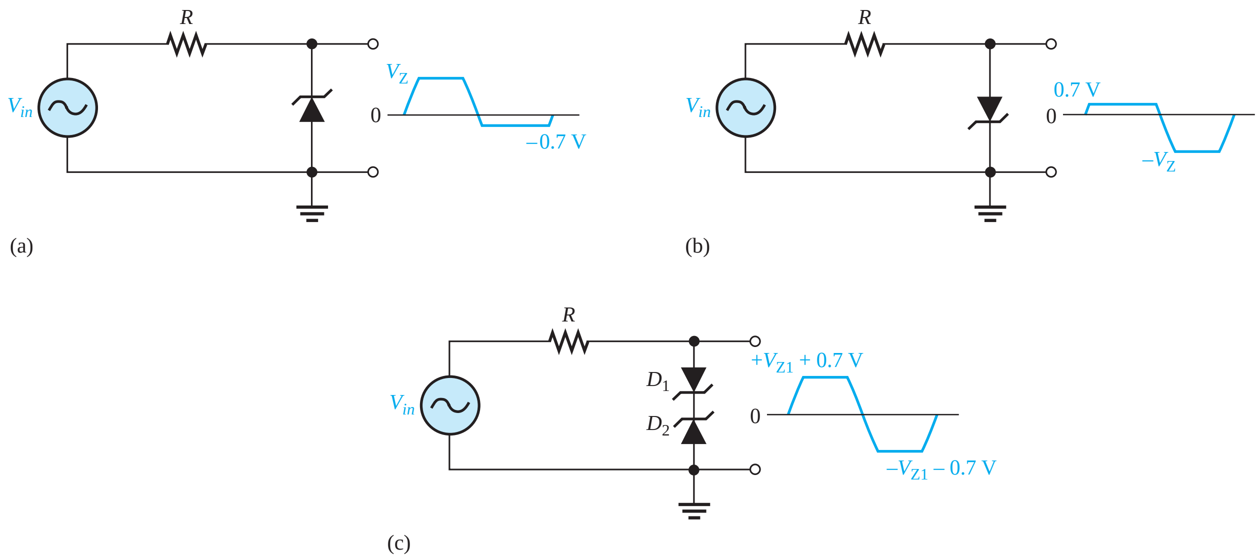


▲ **FIGURE 3–17**

Three-terminal voltage regulators.

Zener Limiter

In addition to voltage regulation applications, zener diodes can be used in ac applications to limit voltage swings to desired levels. Figure 3–18 shows three basic ways the limiting action of a zener diode can be used. Part (a) shows a zener used to limit the positive peak of a signal voltage to the selected zener voltage. During the negative alternation, the zener acts as a forward-biased diode and limits the negative voltage to −0.7 V. When the zener



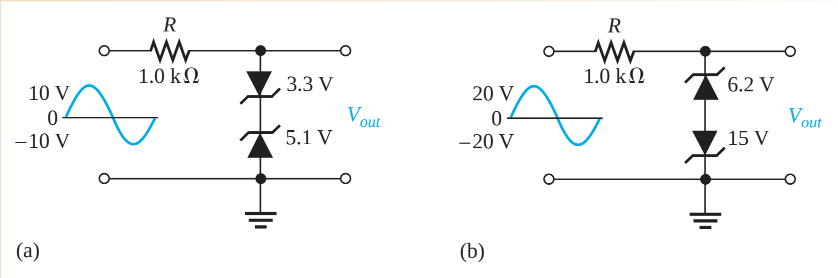
▲ **FIGURE 3–18**

Basic zener limiting action with a sinusoidal input voltage.

is turned around, as in part (b), the negative peak is limited by zener action and the positive voltage is limited to +0.7 V. Two back-to-back zeners limit both peaks to the zener voltage ±0.7 V, as shown in part (c). During the positive alternation, D_2 is functioning as the zener limiter and D_1 is functioning as a forward-biased diode. During the negative alternation, the roles are reversed.

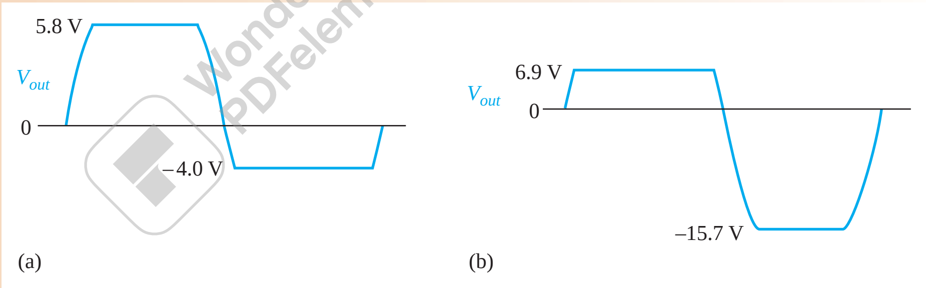
EXAMPLE 3–8

Determine the output voltage for each zener limiting circuit in Figure 3–19.



▲ **FIGURE 3–19**

Solution See Figure 3–20 for the resulting output voltages. Remember, when one zener is operating in breakdown, the other one is forward-biased with approximately 0.7 V across it.



▲ **FIGURE 3–20**

Related Problem

(a) What is the output in Figure 3–19(a) if the input voltage is increased to a peak value of 20 V?

(b) What is the output in Figure 3–19(b) if the input voltage is decreased to a peak value of 5 V?

Open the Multisim file E03-08 in the Examples folder on the companion website. For the specified input voltages, measure the resulting output waveforms. Compare with the waveforms shown in the example.

SECTION 3–2 CHECKUP

1. In a zener diode regulator, what value of load resistance results in the maximum zener current?
2. Explain the terms *no load* and *full load*.
3. How much voltage appears across a zener diode when it is forward-biased?

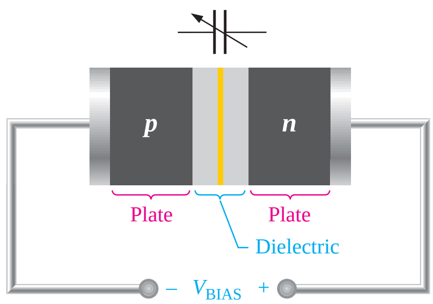
3–3 THE VARACTOR DIODE

The junction capacitance of diodes varies with the amount of reverse bias. Varactor diodes are specially designed to take advantage of this characteristic and are used as voltage-controlled capacitors rather than traditional diodes. These devices are commonly used in communication systems. Varactor diodes are also referred to as *varicaps* or *tuning diodes.*

After completing this section, you should be able to

- **Describe the varactor diode characteristic and analyze its operation**
- Discuss the basic operation of a varactor
  - ◆ Explain why a reverse-biased varactor acts as a capacitor ◆ Calculate varactor capacitance ◆ Identify the varactor schematic symbol
- Interpret a varactor diode datasheet
  - ◆ Define and discuss capacitance tolerance range ◆ Define and discuss capacitance ratio ◆ Discuss the back-to-back configuration
- Discuss and analyze the application of a varactor in a resonant band-pass filter

A **varactor** is a diode that always operates in reverse bias and is doped to maximize the inherent capacitance of the depletion region. The depletion region acts as a capacitor dielectric because of its nonconductive characteristic. The *p* and *n* regions are conductive and act as the capacitor plates, as illustrated in Figure 3–21.



▶ FIGURE 3–21

The reverse-biased varactor diode acts as a variable capacitor.

Basic Operation

Recall that capacitance is determined by the parameters of plate area (A), dielectric constant (ϵ), and plate separation (d), as expressed in the following formula:

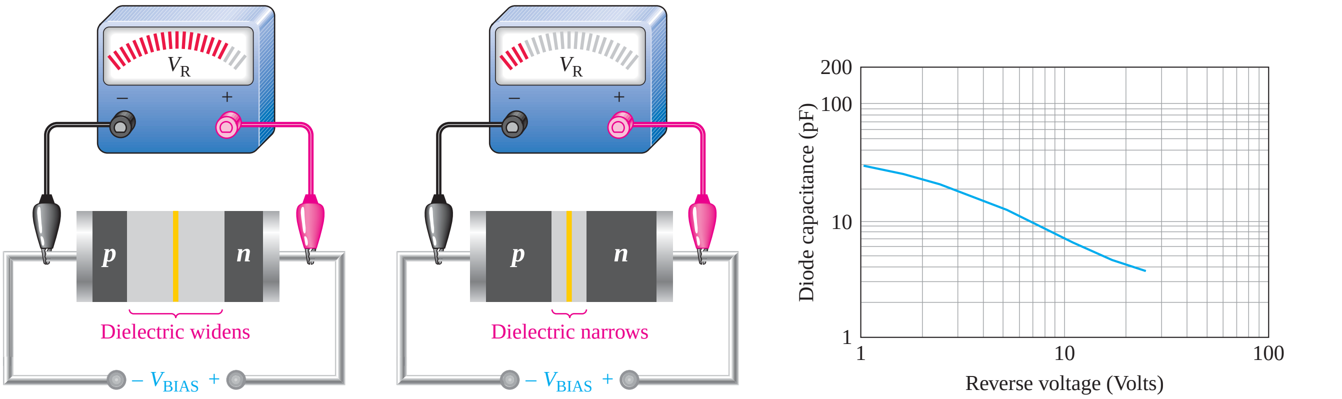
$$C = \frac{A\epsilon}{d}$$

As the reverse-bias voltage increases, the depletion region widens, effectively increasing the plate separation, thus decreasing the capacitance. When the reverse-bias voltage decreases, the depletion region narrows, thus increasing the capacitance. This action is shown in Figure 3–22(a) and (b). A graph of diode capacitance (C_T) versus reverse voltage for a certain varactor is shown in Figure 3–22(c). For this particular device, C_T varies from 30 pF to slightly less than 4 pF as V_R varies from 1 V to 30 V.

In a varactor diode, these capacitance parameters are controlled by the method of doping near the *pn* junction and the size and geometry of the diode's construction. Nominal varactor capacitances are typically available from a few picofarads to several hundred picofarads. Figure 3–23 shows a common symbol for a varactor.

▲ FIGURE 3–23

Varactor diode symbol.



(a) Greater reverse bias, less capacitance (b) Less reverse bias, greater capacitance (c) Example of a diode capacitance versus reverse voltage graph

▲ **FIGURE 3–22**

Varactor diode capacitance varies with reverse voltage.

Varactor Datasheet Information

A partial datasheet for a specific series of varactor diode (Zetex 830 series) is shown in Figure 3–24.

Capacitance Tolerance Range The minimum, nominal, and maximum values of capacitance are shown on the datasheet. For example, when reverse-biased at 3 V, the 832A can

Tuning characteristics at T_{amb} = 25°C

Part	Capacitance (pF)			Min Q V_R = 3V f = 50MHz	Capacitance ratio C_2 / C_{20} @ f = 1MHz	
	Min.	Nom.	Max.		Min.	Max.
829A	7.38	8.2	9.02	250	4.3	5.8
829B	7.79	8.2	8.61	250	4.3	5.8
830A	9.0	10.0	11.0	300	4.5	6.0
830B	9.5	10.0	10.5	300	4.5	6.0
831A	13.5	15.0	16.5	300	4.5	6.0
831B	14.25	15.0	15.75	300	4.5	6.0
832A	19.8	22.0	24.2	200	5.0	6.5
832B	20.9	22.0	23.1	200	5.0	6.5
833A	29.7	33.0	36.3	200	5.0	6.5
833B	31.35	33.0	34.65	200	5.0	6.5
834A	42.3	47.0	51.7	200	5.0	6.5
834B	44.65	47.0	49.35	200	5.0	6.5
835A	61.2	68.0	74.8	100	5.0	6.5
835B	64.6	68.0	71.4	100	5.0	6.5
836A	90.0	100.0	110.0	100	5.0	6.5
836B	95.0	100.0	105.0	100	5.0	6.5

Absolute maximum ratings

Parameter	Symbol	Max.	Unit
Forward current	I_F	200	mA
Power dissipation at T_{amb} = 25°C SOT23	P_{tot}	330	mW
Power dissipation at T_{amb} = 25°C SOD323	P_{tot}	330	mW
Power dissipation at T_{amb} = 25°C SOD523	P_{tot}	250	mW
Operating and storage temperature range		-55 to +150	°C

Electrical characteristics at T_{amb} = 25°C

Paramater	Conditions	Min.	Typ.	Max.	Unit
Reverse breakdown voltage	I_R = 10 A	25			V
Reverse voltage leakage	V_R = 20V		0.2	20	nA
Temperature coefficient of capacitance	V_R = 3V, f = 1MHz		300	400	ppCm/°C

◄ **FIGURE 3–24**

Partial datasheet for the Zetex 830 series varactor diodes. Courtesy of Zetex Semiconductors PLC. Datasheets are available at www.datasheetcatalog/zetexsemiconductors/1/.

exhibit a capacitance anywhere between 19.8 pF and 24.2 pF. This tolerance range should not be confused with the range of capacitance values that result from varying the reverse bias as determined by the capacitance ratio.

Capacitance Ratio The varactor **capacitance ratio** is also known as the *tuning ratio*. It is the ratio of the diode capacitance at a minimum reverse voltage to the diode capacitance at a maximum reverse voltage. For the varactor diodes represented in Figure 3–24, the capacitance ratio is the ratio of C measured at a V_R of 2 V divided by C measured at a V_R of 20 V. The capacitance ratio is designated as C_2/C_{20} in this case.

For the 832A, the minimum capacitance ratio is 5.0. This means that the capacitance value decreases by a factor of 5.0 as V_R is increased from 2 V to 20 V. The following calculation illustrates how to use the capacitance ratio (CR) to find the capacitance range for the 832A. If $C_2 = 22$ pF and the minimum $CR = C_2/C_{20} = 5.0$,

$$C_{20} = \frac{C_2}{CR} = \frac{22\text{ pF}}{5} = 4.4\text{ pF}$$

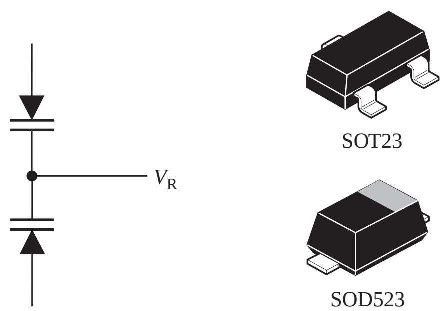
The diode capacitance varies from 22 pF to 4.4 pF when V_R is increased from 2 V to 20 V.

The Zetex 830 series of varactor diodes are hyper-abrupt junction devices. The doping in the *n* and *p* regions is made uniform so that at the *pn* junction there is a very abrupt change from *n* to *p* instead of the more gradual change found in the rectifier diodes. The abruptness of the *pn* junction determines the capacitance ratio.

Back-to-Back Configuration One of the drawbacks of using just a single varactor diode in certain applications, such as rf tuning, is that if the diode is forward-biased by the rf signal during part of the ac cycle, its reverse leakage will increase momentarily. Also, a type of distortion called *harmonic distortion* is produced if the varactor is alternately biased positively and negatively. To avoid harmonic distortion, you will often see two varactor diodes back to back, as shown in Figure 3–25(a) with the reverse dc voltage applied to both devices simultaneously. The two tuning diodes will be driven alternately into high and low capacitance, and the net capacitance will remain constant and is unaffected by the rf signal amplitude. The Zetex 832A varactor diode is available in a back-to-back configuration in an SOT23 package or as a single diode in an SOD523 package, as shown in Figure 3–25(b). Although the cathodes in the back-to-back configuration are connected to a common pin, each diode can also be used individually.

▶ FIGURE 3–25

Varactor diodes and typical packages.



(a) Back-to-back configuration (b)

An Application

A major application of varactors is in tuning circuits. For example, VHF, UHF, and satellite receivers utilize varactors. Varactors are also used in cellular communications. When used in a parallel resonant circuit, as illustrated in Figure 3–26, the varactor acts as a

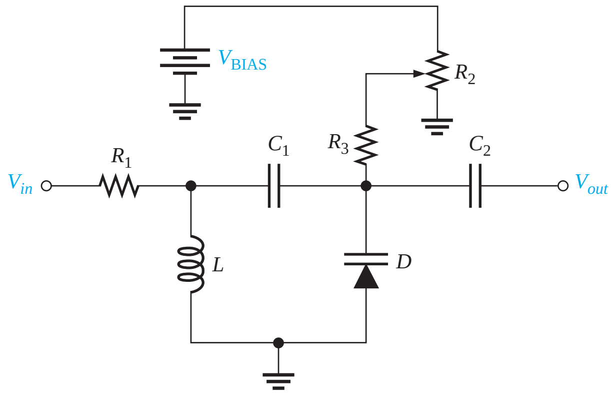


FIGURE 3–26

A resonant band-pass filter using a varactor diode for adjusting the resonant frequency over a specified range.

variable capacitor, thus allowing the resonant frequency to be adjusted by a variable voltage level. The varactor diode provides the total variable capacitance in the parallel resonant band-pass filter. The varactor diode and the inductor form a parallel resonant circuit from the output to ac ground. The capacitors C_1 and C_2 have no effect on the filter's frequency response because their reactances are negligible at the resonant frequencies. C_1 prevents a dc path from the potentiometer wiper back to the ac source through the inductor and R_1. C_2 prevents a dc path from the wiper of the potentiometer to a load on the output. The potentiometer R_2 forms a variable dc voltage for biasing the varactor. The reverse-bias voltage across the varactor can be varied with the potentiometer.

Recall that the parallel resonant frequency is

$$f_r \cong \frac{1}{2\pi\sqrt{LC}}$$

EXAMPLE 3–8

(a) Given that the capacitance of a Zetex 832A varactor is approximately 40 pF at 0 V bias and that the capacitance at a 2 V reverse bias is 22 pF, determine the capacitance at a reverse bias of 20 V using the specified minimum capacitance ratio.

(b) Using the capacitances at bias voltages of 0 V and 20 V, calculate the resonant frequencies at the bias extremes for the circuit in Figure 3–26 if $L = 2$ mH.

(c) Verify the frequency calculations by simulating the circuit in Figure 3–26 for the following component values: $R_1 = 47\ \text{k}\Omega$, $R_2 = 10\ \text{k}\Omega$, $R_3 = 5.1\ \text{M}\Omega$, $C_1 = 10$ nF, $C_2 = 10$ nF, $L = 2$ mH, and $V_{\text{BIAS}} = 20$ V.

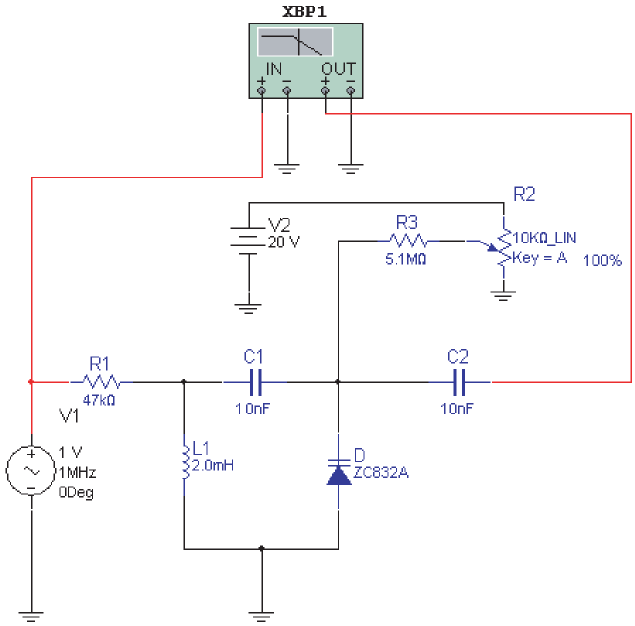
Solution

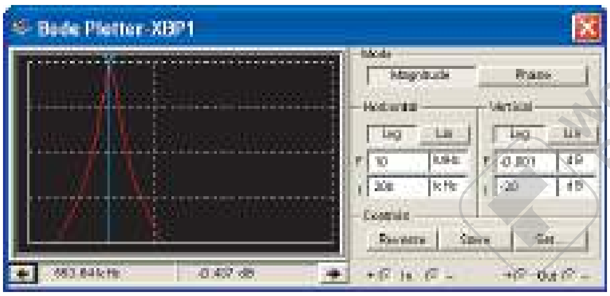
(a) $C_{20} = \dfrac{C_2}{CR} = \dfrac{22\text{ pF}}{5.0} = \mathbf{4.4\ pF}$

(b) $f_0 = \dfrac{1}{2\pi\sqrt{LC}} = \dfrac{1}{2\pi\sqrt{(2\text{ mH})(40\text{ pF})}} = \mathbf{563\ kHz}$

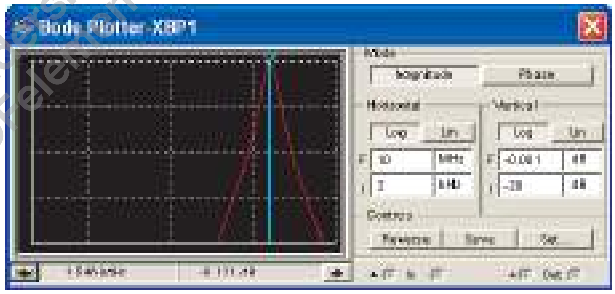
$f_{20} = \dfrac{1}{2\pi\sqrt{LC}} = \dfrac{1}{2\pi\sqrt{(2\text{ mH})(4.4\text{ pF})}} = \mathbf{1.7\ MHz}$

(c) The Multisim simulation of the circuit is shown in Figure 3–27. The Bode plotters show the frequency responses at 0 V and 20 V reverse bias. The center of the 0 V bias response curve is at 553.64 kHz and the center of the 20 V bias response curve is at 1.548 MHz. These results agree reasonably well with the calculated values.





Frequency response for 0 V varactor bias



Frequency response for 20 V reverse varactor bias

▲ **FIGURE 3–27**

Multisim simulation.

These results show that this circuit can be tuned over most of the AM broadcast band.

Related Problem How could you increase the tuning range of the circuit?

SECTION 3–3 CHECKUP

1. What is the key feature of a varactor diode?
2. Under what bias condition is a varactor operated?
3. What part of the varactor produces the capacitance?
4. Based on the graph in Figure 3–22(c), what happens to the diode capacitance when the reverse voltage is increased?
5. Define *capacitance ratio*.

3–4 OPTICAL DIODES

In this section, three types of optoelectronic devices are introduced: the light-emitting diode, quantum dots, and the photodiode. As the name implies, the light-emitting diode is a light emitter. Quantum dots are very tiny light emitters made from silicon with great promise for various devices, including light-emitting diodes. On the other hand, the photodiode is a light detector.

After completing this section, you should be able to

- **Discuss the basic characteristics, operation, and applications of LEDs, quantum dots, and photodiodes**
- Describe the light-emitting diode (LED)
  ◆ Identify the LED schematic symbol ◆ Discuss the process of electroluminescence ◆ List some LED semiconductor materials ◆ Discuss LED biasing ◆ Discuss light emission
- Interpret an LED datasheet
  ◆ Define and discuss radiant intensity and irradiance
- Describe some LED applications
- Discuss high-intensity LEDs and applications
  ◆ Explain how high-intensity LEDs are used in traffic lights ◆ Explain how high-intensity LEDs are used in displays
- Describe the organic LED (OLED)
- Discuss quantum dots and their application
- Describe the photodiode and interpret a typical datasheet
  ◆ Discuss photodiode sensitivity

The Light-Emitting Diode (LED)

The symbol for an LED is shown in Figure 3–28.

The basic operation of the **light-emitting diode (LED)** is as follows. When the device is forward-biased, electrons cross the *pn* junction from the *n*-type material and recombine with holes in the *p*-type material. Recall from Chapter 1 that these free electrons are in the conduction band and at a higher energy than the holes in the valence band. The difference in energy between the electrons and the holes corresponds to the energy of visible light. When recombination takes place, the recombining electrons release energy in the form of **photons.** The emitted light tends to be monochromatic (one color) that depends on the band gap (and other factors). A large exposed surface area on one layer of the semiconductive material permits the photons to be emitted as visible light. This process, called **electroluminescence**, is illustrated in Figure 3–29. Various impurities are added during the doping process to establish the **wavelength** of the emitted light. The wavelength determines the color of visible light. Some LEDs emit photons that are not part of the visible spectrum but have longer wavelengths and are in the **infrared** (IR) portion of the spectrum.

▲ FIGURE 3–28

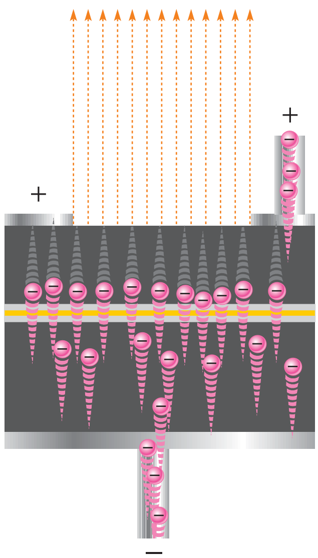
Symbol for an LED. When forward-biased, it emits light.

LED Semiconductor Materials The semiconductor gallium arsenide (GaAs) was used in early LEDs and emits IR radiation, which is invisible. The first visible red LEDs were produced using gallium arsenide phosphide (GaAsP) on a GaAs substrate. The efficiency was increased using a gallium phosphide (GaP) substrate, resulting in brighter red LEDs and also allowing orange LEDs.

Later, GaP was used as the light-emitter to achieve pale green light. By using a red and a green chip, LEDs were able to produce yellow light. The first super-bright red, yellow, and green LEDs were produced using gallium aluminum arsenide phosphide (GaAlAsP). By the early 1990s ultrabright LEDs using indium gallium aluminum phosphide (InGaAlP) were available in red, orange, yellow, and green.

▶ FIGURE 3–29

Electroluminescence in a forward-biased LED.



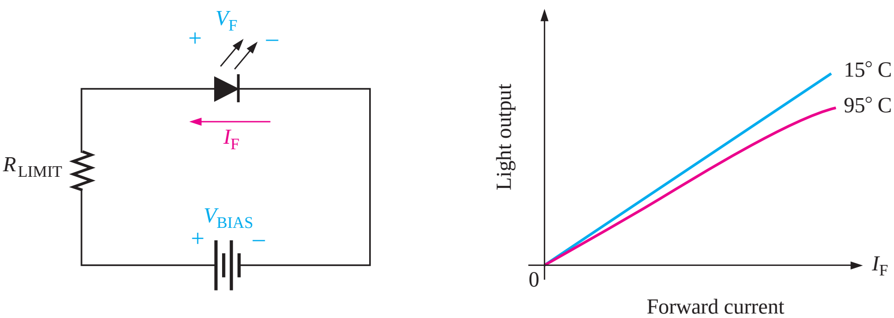
FYI

Efficiency is a term used in many fields to show how well a particular process works. It is the ratio of the output to the input and is a dimensionless number, often expressed as a percentage. An efficiency of 100% is the theoretical maximum that can never be achieved in real systems. For lighting, the term *efficacy* is used with units of lumens per watt and is related to the efficiency of converting input power (in watts) to light that can be seen by the human eye (lumens). The theoretical maximum efficacy is 683 lumens/watt.

Blue LEDs using silicon carbide (SiC) and ultrabright blue LEDs made of gallium nitride (GaN) became available. High intensity LEDs that produce green and blue are also made using indium gallium nitride (InGaN). High-intensity white LEDs are formed using ultrabright blue GaN coated with fluorescent phosphors that absorb the blue light and reemit it as white light.

LED Biasing The forward voltage across an LED is considerably greater than for a silicon diode. Typically, the maximum V_F for LEDs is between 1.2 V and 3.2 V, depending on the material. Reverse breakdown for an LED is much less than for a silicon rectifier diode (3 V to 10 V is typical).

The LED emits light in response to a sufficient forward current, as shown in Figure 3–30(a). The amount of power output translated into light is directly proportional to the forward current, as indicated in Figure 3–30(b). An increase in I_F corresponds proportionally to an increase in light output. The light output (both intensity and color) is also dependent on temperature. Light intensity goes down with higher temperature as indicated in the figure.



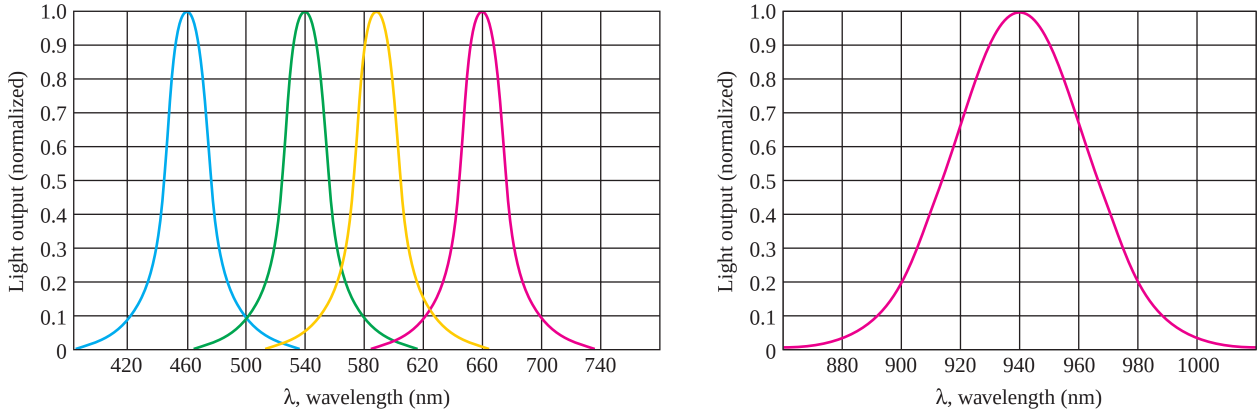
(a) Forward-biased operation

(b) General light output versus forward current for two temperatures

▲ FIGURE 3–30

Basic operation of an LED.

Light Emission An LED emits light over a specified range of wavelengths as indicated by the **spectral** output curves in Figure 3–31. The curves in part (a) represent the light output versus wavelength for typical visible LEDs, and the curve in part (b) is for a typical infrared LED. The wavelength (λ) is expressed in nanometers (nm). The normalized output of the visible red LED peaks at 660 nm, the yellow at 590 nm, green at 540 nm, and blue at 460 nm. The output for the infrared LED peaks at 940 nm.

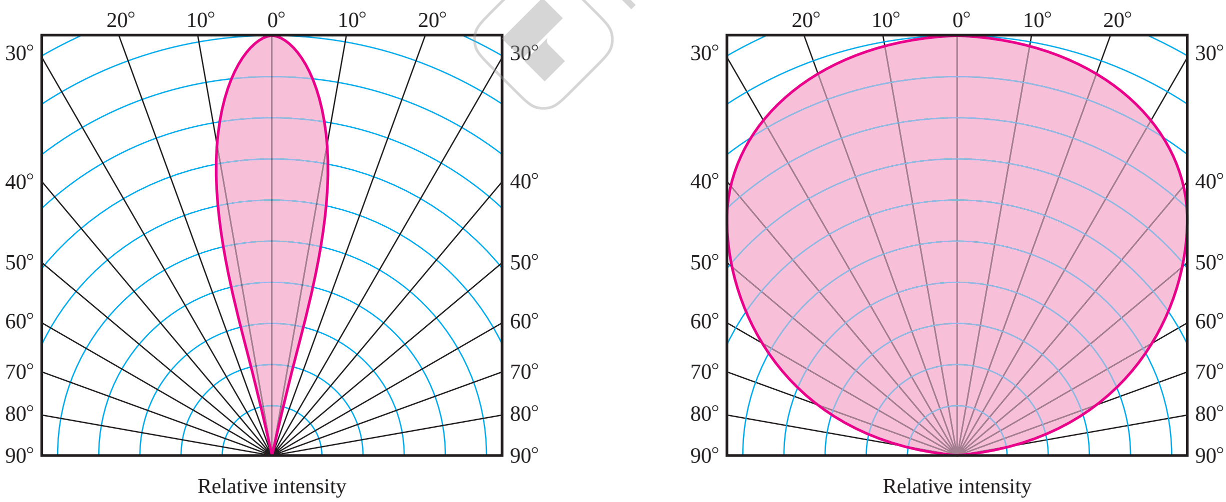


(a) Visible light (b) Infrared (IR)

▲ **FIGURE 3–31**

Examples of typical spectral output curves for LEDs.

The graphs in Figure 3–32 show typical **radiation** patterns for small LEDs. LEDs are directional light sources (unlike filament or fluorescent bulbs). The radiation pattern is generally perpendicular to the emitting surface; however, it can be altered by the shape of the emitter surface and by lenses and diffusion films to favor a specific direction. Directional patterns can be an advantage for certain applications, such as traffic lights, where the light is intended to be seen only by certain drivers. Figure 3–32(a) shows the pattern for a forward-directed LED such as used in small panel indicators. Figure 3–32(b) shows the pattern for a wider viewing angle such as found in many super-bright LEDs. A wide variety of patterns are available from manufacturers; one variation is to design the LED to emit nearly all the light to the side in two lobes.



(a) A narrow viewing angle LED (b) A wide viewing angle LED

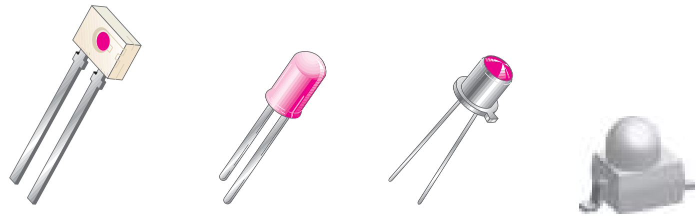
▲ **FIGURE 3–32**

Radiation patterns for two different LEDs.

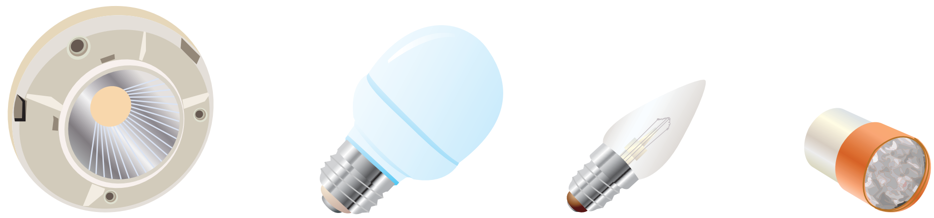
Typical small LEDs for indicators are shown in Figure 3–33(a). In addition to small LEDs for indicators, bright LEDs are becoming popular for lighting because of their superior efficiency and long life. A typical LED for lighting can deliver 50–60 lumens per watt, which is approximately five times greater efficiency than a standard incandescent bulb. LEDs for lighting are available in a variety of configurations, including even flexible tubes for decorative lighting and low-wattage bulbs for outdoor walkways and gardens. Many

FIGURE 3–33

Typical LEDs.



(a) Typical small LEDs for indicators



Helion 12 V overhead light with socket and module

120 V, 3.5 W screw base for low-level illumination

120 V, 1 W small screw base candelabra style

6 V, bayonet base for flashlights, etc.

(b) Typical LEDs for lighting applications

LED lamps are designed to work in 120 V standard fixtures. A few representative configurations are shown in Figure 3–33(b).

LED Datasheet Information

A partial datasheet for an TSMF1000 infrared (IR) light-emitting diode is shown in Figure 3–34. Notice that the maximum reverse voltage is only 5 V, the maximum forward current is 100 mA, and the forward voltage drop is approximately 1.3 V for $I_F = 20$ mA.

From the graph in part (c), you can see that the peak power output for this device occurs at a wavelength of 870 nm; its radiation pattern is shown in part (d).

Radiant Intensity and Irradiance In Figure 3–34(a), the **radiant intensity,** I_e (symbol not to be confused with current), is the output power per steradian and is specified as 5 mW/sr at $I_F = 20$ mA. The steradian (sr) is the unit of solid angular measurement. **Irradiance,** E, is the power per unit area at a given distance from an LED source expressed in mW/cm^2. Irradiance is important because the response of a detector (photodiode) used in conjunction with an LED depends on the irradiance of the light it receives.

EXAMPLE 3–10

From the LED datasheet in Figure 3–34 determine the following:

(a) The radiant power at 910 nm if the maximum output is 35 mW.

(b) The forward voltage drop for $I_F = 20$ mA.

(c) The radiant intensity for $I_F = 40$ mA.

Solution

(a) From the graph in Figure 3–34(c), the relative radiant power at 910 nm is approximately 0.25 and the peak radiant power is 35 mW. Therefore, the radiant power at 910 nm is

$$\phi_e = 0.25(35\text{ mW}) = \mathbf{8.75\text{ mW}}$$

(b) From the graph in part (b), $V_F \cong$ **1.25 V** for $I_F = 20$ mA.

(c) From the graph in part (e), $I_e \cong$ **10 mW/sr** for $I_F = 40$ mA.

Related Problem Determine the relative radiant power at 850 nm.

Absolute Maximum Ratings

T_{amb} = 25°C, unless otherwise specified

Parameter	Test condition	Symbol	Value	Unit
Reverse Voltage		V_R	5	V
Forward current		I_F	100	mA
Peak Forward Current	t_p/T = 0.5, t_p = 100 µs	I_{FM}	200	mA
Surge Forward Current	t_p = 100 µs	I_{FSM}	0.8	A
Power Dissipation		P_V	190	mW
Junction Temperature		T_j	100	°C
Operating Temperature Range		T_{amb}	- 40 to + 85	°C

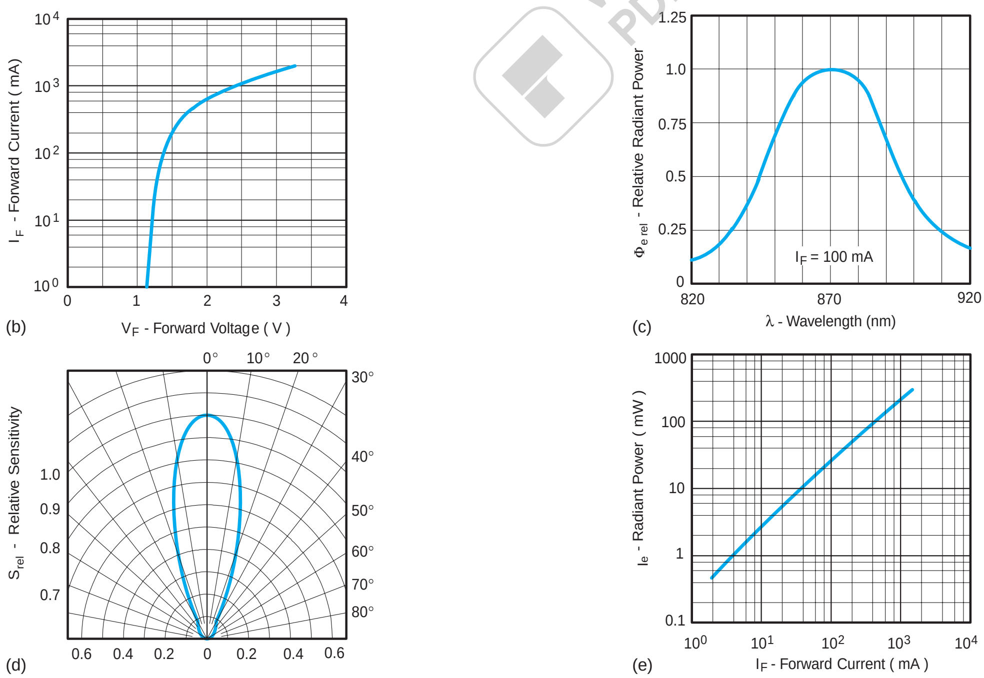
Basic Characteristics

T_{amb} = 25°C, unless otherwise specified

T_{amb} = 25°C, unless otherwise specified

Parameter	Test condition	Symbol	Min	Typ.	Max	Unit
Forward Voltage	I_F = 20 mA	V_F		1.3	1.5	V
	I_F = 1 A, t_p = 100 µs	V_F		2.4		V
Temp. Coefficient of V_F	I_F = 1.0 mA	TK_{VF}		- 1.7		mV/K
Reverse Current	V_R = 5 V	I_R			10	µA
Junction capacitance	V_R = 0 V, f = 1 MHz, E = 0	C_j		160		pF
Radiant Intensity	I_F = 20 mA	I_e	2.5	5	13	mW/sr
	I_F = 100 mA, t_p = 100 µs	I_e		25		mW/sr
Radiant Power	I_F = 100 mA, t_p = 20 ms	ϕ_e		35		mW
Temp. Coefficient of ϕ_e	I_F = 20 mA	$TK\phi_e$		- 0.6		%/K
Angle of Half Intensity		ϕ		± 17		deg
Peak Wavelength	I_F = 20 mA	λ_p		870		nm
Spectral Bandwidth	I_F = 20 mA	$\Delta\lambda$		40		nm
Temp. Coefficient of λ_p	I_F = 20 mA	$TK\lambda_p$		0.2		nm/K
Rise Time	I_F = 20 mA	t_r		30		ns
Fall Time	I_F = 20 mA	t_f		30		ns
Virtual Source Diameter		∅		1.2		mm

(a)

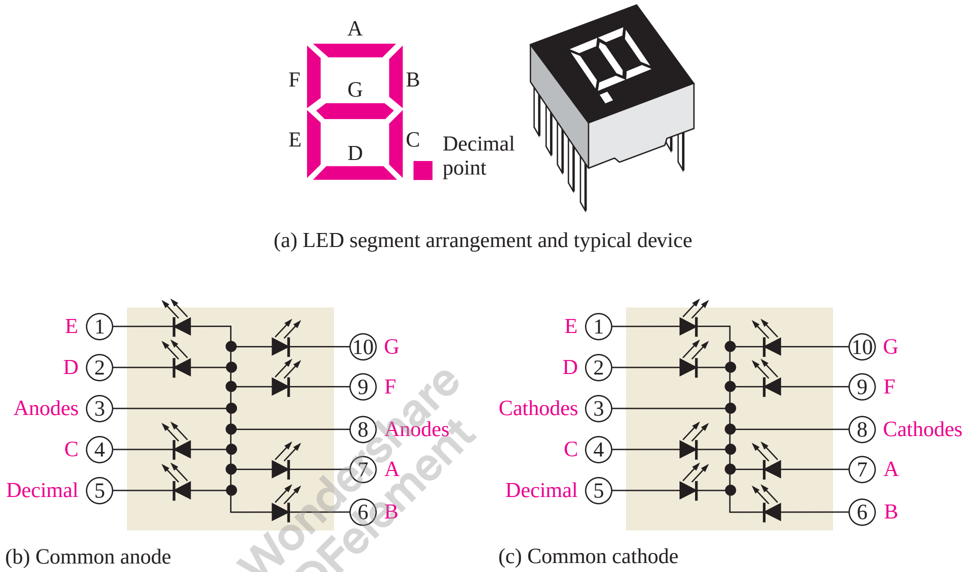


▲ **FIGURE 3–34**

Partial datasheet for an TSMF1000 IR light-emitting diode. Datasheet courtesy of Vishay Intertechnology, Inc. Datasheets are available at www.vishay.com.

Applications

Standard LEDs are used for indicator lamps and readout displays on a wide variety of instruments, ranging from consumer appliances to scientific apparatus. A common type of display device using LEDs is the seven-segment display. Combinations of the segments form the ten decimal digits as illustrated in Figure 3–35. Each segment in the display is an LED. By forward-biasing selected combinations of segments, any decimal digit and a decimal point can be formed. Two types of LED circuit arrangements are the common anode and common cathode as shown.



▲ **FIGURE 3–35**

The 7-segment LED display.

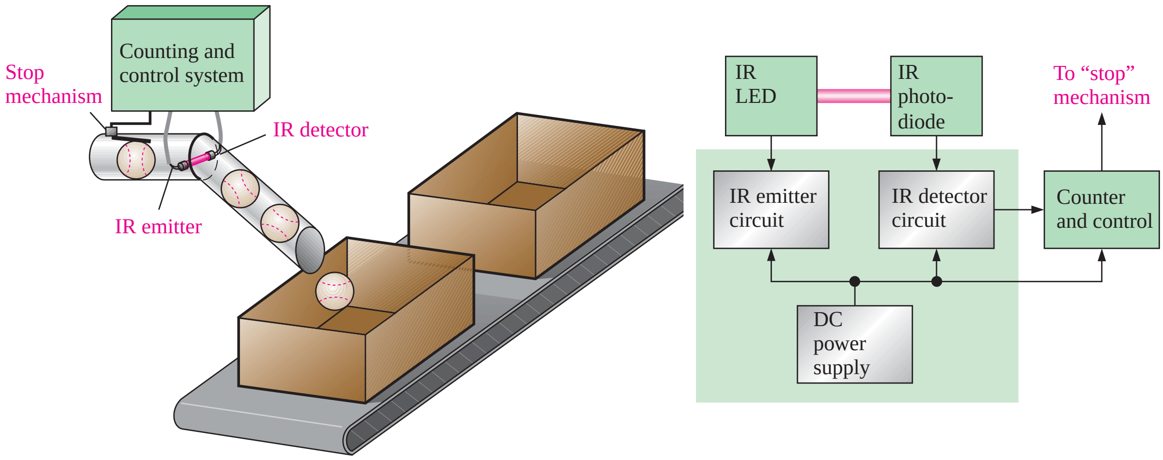
One common application of an infrared LED is in remote control units for TV, DVD, gate openers, etc. The IR LED sends out a beam of invisible light that is sensed by the receiver in your TV, for example. For each button on the remote control unit, there is a unique code. When a specific button is pressed, a coded electrical signal is generated that goes to the LED, which converts the electrical signal to a coded infrared light signal. The TV receiver recognizes the code and takes appropriate action, such as changing the channel or increasing the volume.

Also, IR light-emitting diodes are used in optical coupling applications, often in conjunction with fiber optics. Areas of application include industrial processing and control, position encoders, bar graph readers, and optical switching.

An example of how an IR LED could be used in an industrial application is illustrated in Figure 3–36. This particular system is used to count baseballs as they are fed down a chute into a box for shipping. As each ball passes through the chute, the IR beam emitted by the LED is interrupted. This is detected by the photodiode (discussed later) and the resulting change in current is sensed by a detector circuit. An electronic circuit counts each time that the beam is interrupted; and when a preset number of balls pass through the chute, the "stop" mechanism is activated to stop the flow of balls until the next empty box is automatically moved into place on the conveyor. When the next box is in place, the "stop" mechanism is deactivated and the balls begin to roll again. This idea can also be applied to inventory and packing control for many other types of products.

High-Intensity LEDs

LEDs that produce much greater light outputs than standard LEDs are found in many applications including traffic lights, automotive lighting, indoor and outdoor advertising and informational signs, and home lighting.



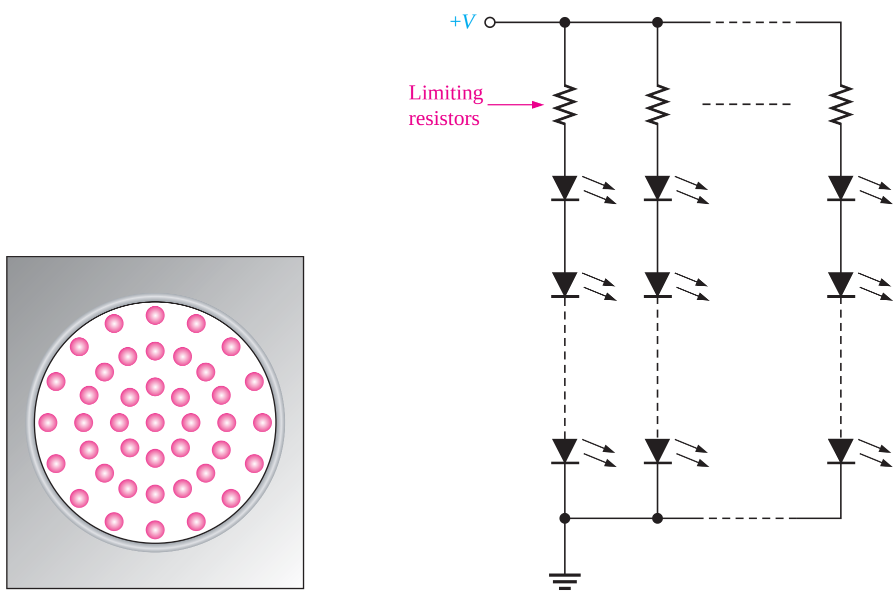
▲ **FIGURE 3–36**

Basic concept and block diagram of a counting and control system.

Traffic Lights LEDs are quickly replacing the traditional incandescent bulbs in traffic signal applications. Arrays of tiny LEDs form the red, yellow, and green lights in a traffic light unit. An LED array has three major advantages over the incandescent bulb: brighter light, longer lifetime (years vs. months), and less energy consumption (about 90% less).

LED traffic lights are constructed in arrays with lenses that optimize and direct the light output. Figure 3–37(a) illustrates the concept of a traffic light array using red LEDs. A relatively low density of LEDs is shown for illustration. The actual number and spacing of the LEDs in a traffic light unit depends on the diameter of the unit, the type of lens, the color, and the required light intensity. With an appropriate LED density and a lens, an 8- or 12-inch traffic light will appear essentially as a solid-color circle.

LEDs in an array are usually connected either in a series-parallel or a parallel arrangement. A series connection is not practical because if one LED fails open, then all the LEDs are disabled. For a parallel connection, each LED requires a limiting resistor. To reduce the number of limiting resistors, a series-parallel connection can be used, as shown in Figure 3–37(b).



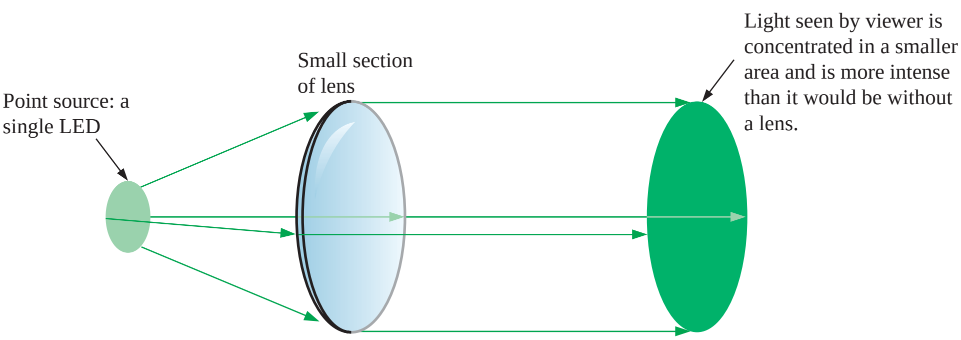
(a) LED array (b) Circuit

▲ **FIGURE 3–37**

LED traffic light.

▶ **FIGURE 3–38**

The lens directs the light emitted from the LED to optimize visibility.

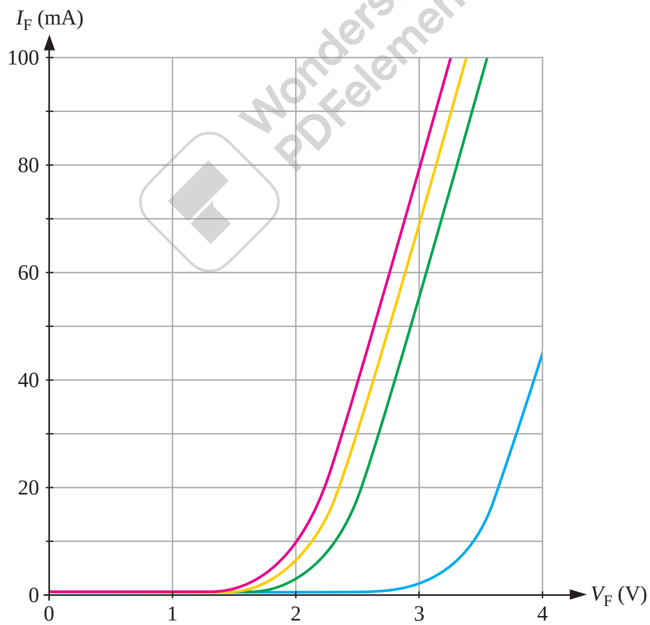


Some LED traffic arrays use small reflectors for each LED to help maximize the effect of the light output. Also, an optical lens covers the front of the array to direct the light from each individual diode to prevent improper dispersion of light and to optimize the visibility. Figure 3–38 illustrates how a lens is used to direct the light toward the viewer.

The particular LED circuit configuration depends on the voltage and the color of the LED. Different color LEDs require different forward voltages to operate. Red LEDs take the least; and as the color moves up the color spectrum toward blue, the voltage requirement increases. Typically, a red LED requires about 2 V, while blue LEDs require between 3 V and 4 V. Generally, LEDs, however, need 20 mA to 30 mA of current, regardless of their voltage requirements. Typical *V-I* curves for red, yellow, green, and blue LEDs are shown in Figure 3–39.

▶ **FIGURE 3–39**

***V-I* characteristic curves for visible-light LEDs.**



EXAMPLE 3–11

Using the graph in Figure 3–39, determine the green LED forward voltage for a current of 20 mA. Design a 12 V LED circuit to minimize the number of limiting resistors for an array of 60 diodes.

Solution From the graph, a green LED has a forward voltage of approximately 2.5 V for a forward current of 20 mA. The maximum number of series LEDs is 3. The total voltage across three LEDs is

$$V = 3 \times 2.5\text{ V} = 7.5\text{ V}$$

The voltage drop across the series-limiting resistor is

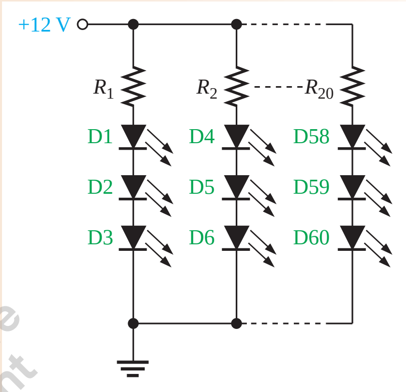
$$V = 12\text{ V} - 7.5\text{ V} = 4.5\text{ V}$$

The value of the limiting resistor is

$$R_{\text{LIMIT}} = \frac{4.5\text{ V}}{20\text{ mA}} = 225\ \Omega$$

The LED array has 20 parallel branches each with a limiting resistor and three LEDs, as shown in Figure 3–40.

▶ FIGURE 3–40



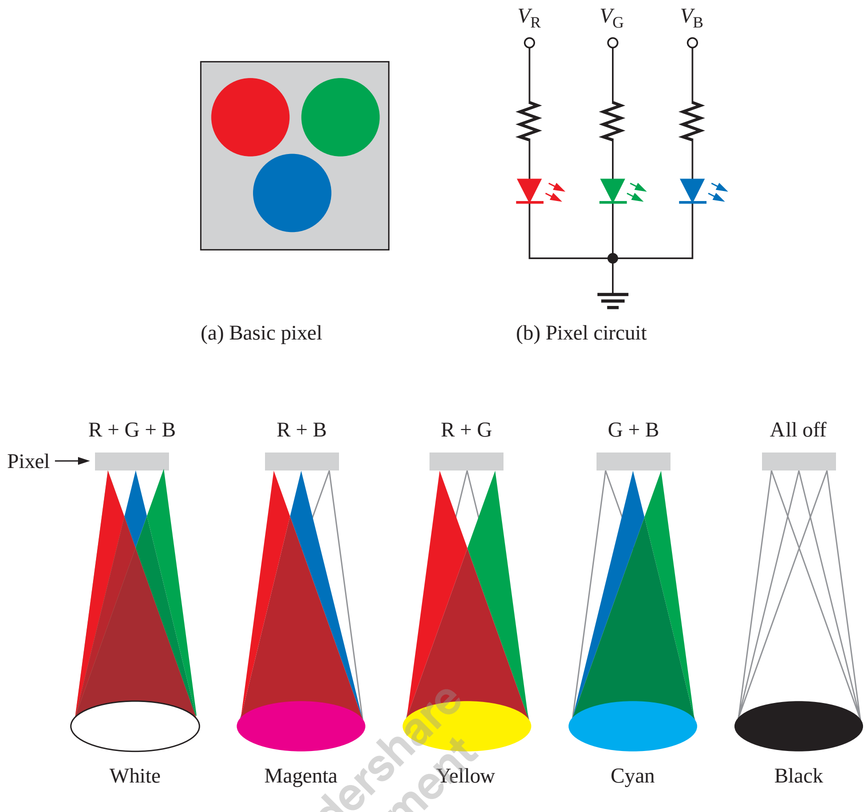
Related Problem Design a 12 V red LED array with minimum limiting resistors, a forward current of 30 mA, and containing 64 diodes.

LED Displays LEDs are widely used in large and small signs and message boards for both indoor and outdoor uses, including large-screen television. Signs can be single-color, multicolor, or full-color. Full-color screens use a tiny grouping of high-intensity red, green, and blue LEDs to form a **pixel**. A typical screen is made of thousands of RGB pixels with the exact number determined by the sizes of the screen and the pixel.

Red, green, and blue (RGB) are primary colors and when mixed together in varying amounts, can be used to produce any color in the visible spectrum. A basic pixel formed by three LEDs is shown in Figure 3–41. The light emission from each of the three diodes can be varied independently by varying the amount of forward current. Yellow is added to the three primary colors (RGBY) in some TV screen applications.

Other Applications High-intensity LEDs are becoming more widely used in automotive lighting for taillights, brakelights, turn signals, back-up lights, and interior applications. LED arrays are expected to replace most incandescent bulbs in automotive lighting. Eventually, headlights may also be replaced by white LED arrays. LEDs can be seen better in poor weather and can last 100 times longer than an incandescent bulb.

LEDs are also finding their way into interior home and business lighting applications. Arrays of white LEDs may eventually replace incandescent light bulbs and flourescent lighting in interior living and work areas. As previously mentioned, most white LEDs use a blue GaN (gallium nitride) LED covered by a yellowish phosphor coating made of a certain type of crystals that have been powdered and bound in a type of viscous adhesive. Since yellow light stimulates the red and green receptors of the eye, the resulting mix of blue and yellow light gives the appearance of white.



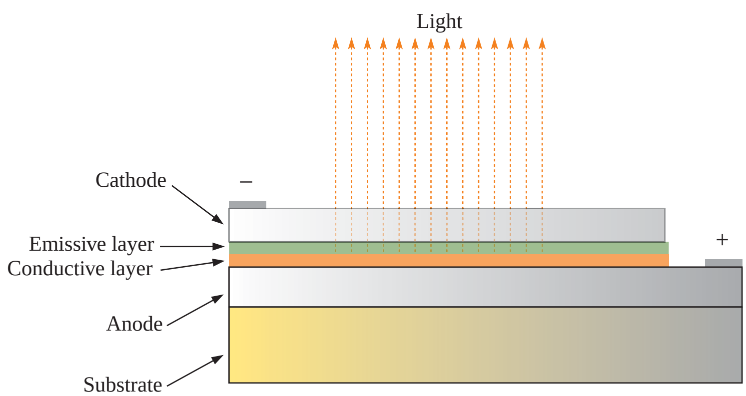
(c) Examples of different combinations of equal amounts of primary colors

▲ FIGURE 3–41

The concept of an RGB pixel used in LED display screens.

The Organic LED (OLED)

An **OLED** is a device that consists of two or three layers of materials composed of organic molecules or polymers that emit light with the application of voltage. OLEDs produce light through the process of electrophosphorescence. The color of the light depends on the type of organic molecule in the emissive layer. The basic structure of a 2-layer OLED is shown in Figure 3–42.



▲ FIGURE 3–42

Basic structure of a top-emitting 2-layer OLED.

Electrons are provided to the emissive layer and removed from the conductive layer when there is current between the cathode and anode. This removal of electrons from the conductive layer leaves holes. The electrons from the emissive layer recombine with the holes from the conductive layer near the junction of the two layers. When this recombination occurs, energy is released in the form of light that passes through the transparent cathode material. If the anode and substrate are also made from transparent materials, light is emitted in both directions, making the OLED useful in applications such as heads-up displays.

OLEDs can be sprayed onto substrates just like inks are sprayed onto paper during printing. Inkjet technology greatly reduces the cost of OLED manufacturing and allows OLEDs to be printed onto very large films for large displays like 80-inch TV screens or electronic billboards.

FYI

OLED technology was developed by Eastman Kodak. It is beginning to replace LCD (liquid crystal display) technology in handheld devices such as PDAs and cellular phones. OLEDs are brighter, thinner, faster, and lighter than conventional LEDs or LCDs. They also use less power and are cheaper to manufacture.

Quantum Dots

Quantum dots are a form of nanocrystals that are made from semiconductor material such as silicon, germanium, cadmium sulfide, cadmium selenide, and indium phosphide. Quantum dots are only 1 nm to 12 nm in diameter (a nm is one billionth of a meter). Billions of dots could fit on the head of a pin! Because of their small size, quantum effects arise due to the confinement of electrons and holes; as a result, material properties are very different than the normal material. One important property is that the band gap is dependent on the size of the dots. When excited from an external source, dots formed from semiconductors emit light in the visible range as well as infrared and ultraviolet, depending on their size. The higher-frequency blue light is emitted by smaller dots suspended in solution (larger band gap); red light is emitted from solutions with larger dots (smaller band gap). Solutions containing the quantum dots glow eerily with specific colors as shown in the photograph in Figure 3–43.

◀ FIGURE 3–43

Solutions containing quantum dots glow with specific colors that depend on the size of the dots. Courtesy of NN-Labs.

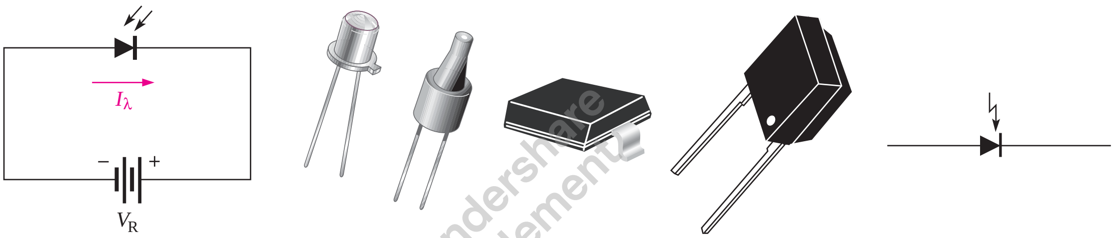
Although quantum dots are not diodes themselves, they can be used in construction of light-emitting diodes as well as display devices and a variety of other applications. As you know, LEDs work by generating a specific frequency (color) of light, which is determined by the band gap. To produce white light, blue LEDs are coated with a phosphor that adds yellow light to the blue, forming white. The result is not a pure white, but tends to be harsh and makes colors appear unnatural. While this is satisfactory for displays and signs, many people do not like it for home lighting.

Quantum dots can be used to modify the basic color of LEDs by converting higher energy photons (blue) to photons of lower energy. The result is a color that more closely approximates an incandescent bulb. Quantum dot filters can be designed to contain combinations of colors, giving designers control of the spectrum. The important advantage of quantum dot technology is that it does not lose the incoming light; it merely absorbs the light and reradiates it at a different frequency. This enables control of color without giving up efficiency. By placing a quantum dot filter in front of a white LED, the spectrum can be made to look like that of an incandescent bulb. The resulting light is more satisfactory for general illumination, while retaining the advantages of LEDs.

There are other promising applications, particularly in medical applications. Water-soluble quantum dots are used as a biochemical luminescent marker for cellular imaging and medical research. Research is also being done on quantum dots as the basic device units for information processing by manipulating two energy levels within the quantum dot.

The Photodiode

The **photodiode** is a device that operates in reverse bias, as shown in Figure 3–44(a), where I_λ is the reverse light current. The photodiode has a small transparent window that allows light to strike the *pn* junction. Some typical photodiodes are shown in Figure 3–44(b). An alternate photodiode symbol is shown in Figure 3–44(c).



(a) Reverse-bias operation using standard symbol (b) Typical devices (c) Alternate symbol

▲ FIGURE 3–44

Photodiode.

Recall that when reverse-biased, a rectifier diode has a very small reverse leakage current. The same is true for a photodiode. The reverse-biased current is produced by thermally generated electron-hole pairs in the depletion region, which are swept across the *pn* junction by the electric field created by the reverse voltage. In a rectifier diode, the reverse leakage current increases with temperature due to an increase in the number of electron-hole pairs.

A photodiode differs from a rectifier diode in that when its *pn* junction is exposed to light, the reverse current increases with the light intensity. When there is no incident light, the reverse current, I_λ, is almost negligible and is called the **dark current.** An increase in the amount of light intensity, expressed as irradiance (mW/cm^2), produces an increase in the reverse current, as shown by the graph in Figure 3–45(a).

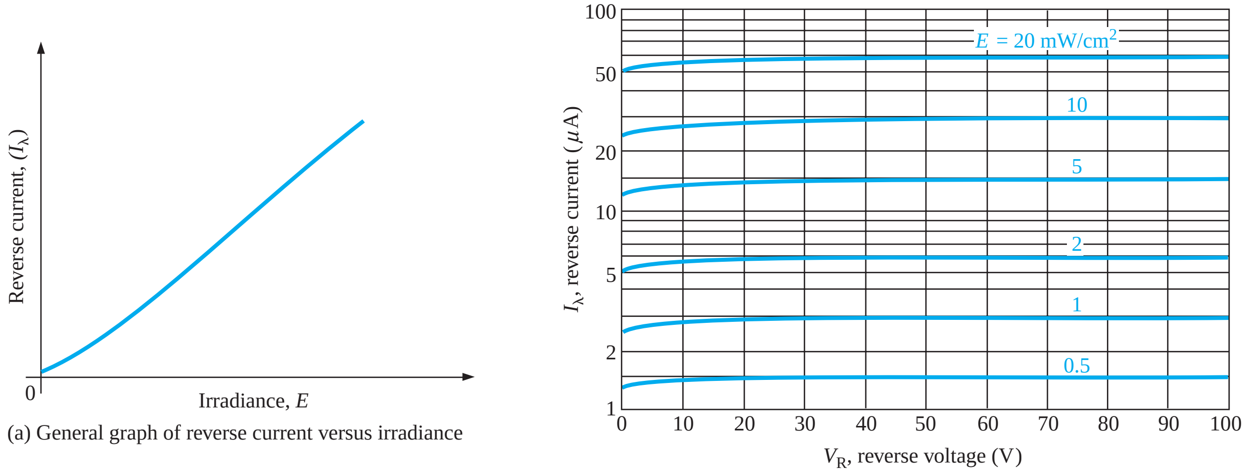
From the graph in Figure 3–45(b), you can see that the reverse current for this particular device is approximately 1.4 μA at a reverse-bias voltage of 10 V with an irradiance of 0.5 mW/cm^2. Therefore, the resistance of the device is

$$R_R = \frac{V_R}{I_\lambda} = \frac{10\text{ V}}{1.4\ \mu\text{A}} = 7.14\text{ M}\Omega$$

At 20 mW/cm^2, the current is approximately 55 μA at $V_R = 10$ V. The resistance under this condition is

$$R_R = \frac{V_R}{I_\lambda} = \frac{10\text{ V}}{55\ \mu\text{A}} = 182\text{ k}\Omega$$

These calculations show that the photodiode can be used as a variable-resistance device controlled by light intensity.



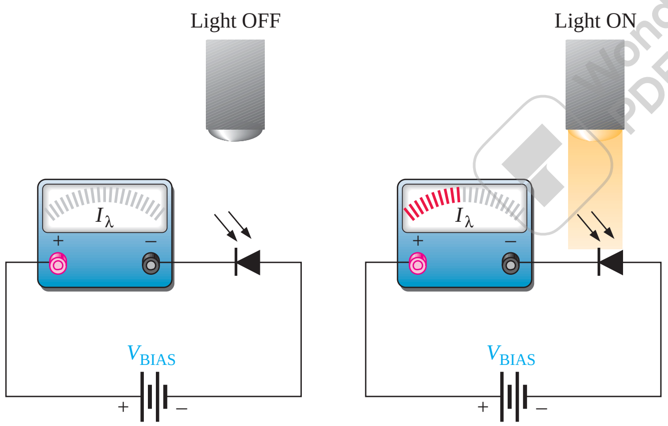
(a) General graph of reverse current versus irradiance

(b) Example of a graph of reverse current versus reverse voltage for several values of irradiance

▲ **FIGURE 3–45**

Typical photodiode characteristics.

Figure 3–46 illustrates that the photodiode allows essentially no reverse current (except for a very small dark current) when there is no incident light. When a light beam strikes the photodiode, it conducts an amount of reverse current that is proportional to the light intensity (irradiance).



(a) No light, no current except negligible dark current

(b) Where there is incident light, resistance decreases and there is reverse current.

▲ **FIGURE 3–46**

Operation of a photodiode.

Photodiode Datasheet Information

A partial datasheet for an TEMD1000 photodiode is shown in Figure 3–47. Notice that the maximum reverse voltage is 60 V and the dark current (reverse current with no light) is typically 1 nA for a reverse voltage of 10 V. The dark current increases with an increase in reverse voltage and also with an increase in temperature.

Sensitivity From the graph in part (b), you can see that the maximum sensitivity for this device occurs at a wavelength of 950 nm. The angular response graph in part (c) shows an area of response measured as relative sensitivity. At 10° on either side of the maximum orientation, the sensitivity drops to approximately 82% of maximum.

Absolute Maximum Ratings

T_{amb} = 25°C, unless otherwise specified

Parameter	Test condition	Symbol	Value	Unit
Reverse Voltage		V_R	60	V
Power Dissipation	$T_{amb} \leq 25°C$	P_V	75	mW
Junction Temperature		T_j	100	°C
Storage Temperature Range		T_{stg}	- 40 to + 100	°C
Operating Temperature Range		T_{stg}	- 40 to + 85	°C
Soldering Temperature	$t \leq 5$ s	T_{sd}	< 260	°C

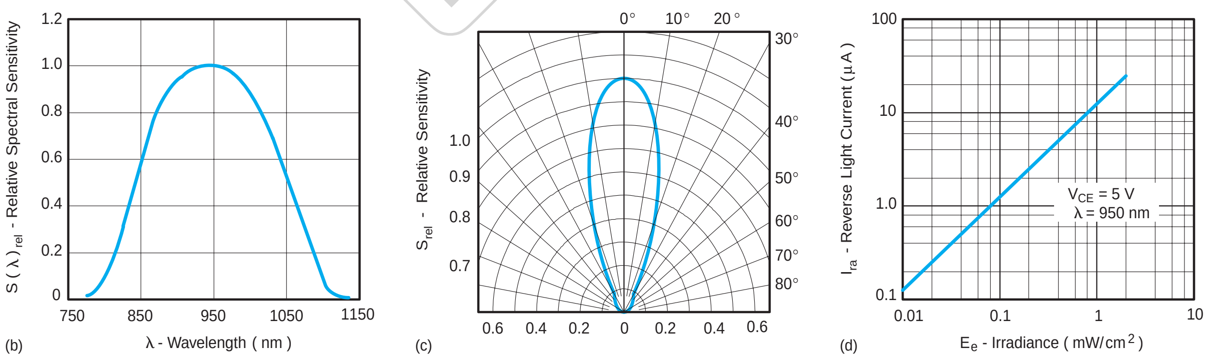
Basic Characteristics

T_{amb} = 25 °C, unless otherwise specified
T_{amb} = 25 °C, unless otherwise specified

Parameter	Test condition	Symbol	Min	Typ.	Max	Unit
Forward Voltage	I_F = 50 mA	V_F		1.0	1.3	V
Breakdown Voltage	I_R = 100 µA, E = 0	$V_{(BR)}$	60			V
Reverse Dark Current	V_R = 10 V, E = 0	I_{ro}		1	10	nA
Diode capacitance	V_R = 5 V, f = 1 MHz, E = 0	C_D		1.8		pF
Reverse Light Current	E_e = 1 mW/cm^2, λ = 870 nm, V_R = 5 V	I_{ra}		10		µA
	E_e = 1 mW/cm^2, λ = 950 nm, V_R = 5 V	I_{ra}	5	12		µA

Parameter	Test condition	Symbol	Min	Typ.	Max	Unit
Temp. Coefficient of I_{ra}	V_R = 5 V, = 870 nm	TK_{Ira}		0.2		%/K
Absolute Spectral Sensitivity	V_R = 5 V, = 870 nm	s(λ)		0.60		A/W
	V_R = 5 V, = 950 nm	s(λ)		0.55		A/W
Angle of Half Sensitivity		ϕ		±15		deg
Wavelength of Peak Sensitivity		λ_p		900		nm
Range of Spectral Bandwidth		$\lambda_{0.5}$		840 to 1050		nm
Rise Time	V_R = 10 V, R_L = 50, Ω λ = 820 nm	t_r		4		ns
Fall Time	V_R = 10 V, R_L = 50, Ω λ = 820 nm	t_f		4		ns

(a)



▲ **FIGURE 3–47**

Partial datasheet for the TEMD1000 photodiode. Datasheet courtesy of Vishay Intertechnology, Inc.

EXAMPLE 3–12 For a TEMD1000 photodiode,

(a) Determine the maximum dark current for $V_R = 10$ V.

(b) Determine the reverse light current for an irradiance of 1 mW/cm^2 at a wavelength of 850 nm if the device angle is oriented at 10° with respect to the maximum irradiance and the reverse voltage is 5 V.

Solution **(a)** From Figure 3–47(a), the maximum dark current $I_{ro} = \mathbf{10\ nA.}$

(b) From the graph in Figure 3–47(d), the reverse light current is 12 μ A at 950 nm. From Figure 3–47(b), the relative sensitivity is 0.6 at 850 nm. Therefore, the reverse light current is

$$I_\lambda = I_{ra} = 0.6(12\ \mu\text{A}) = 72\ \mu\text{A}$$

For an angle of 10°, the relative sensitivity is reduced to 0.92 of its value at 0°.

$$I_\lambda = I_{ra} = 0.92\,(7.2\ \mu\text{A}) = \mathbf{6.62\ \mu A}$$

Related Problem What is the reverse current if the wavelength is 1050 nm and the angle is 0°?

SECTION 3–4 CHECKUP

1. Name two types of LEDs in terms of their light-emission spectrum.
2. Which has the greater wavelength, visible light or infrared?
3. In what bias condition is an LED normally operated?
4. What happens to the light emission of an LED as the forward current increases?
5. The forward voltage drop of an LED is 0.7 V. (true or false)
6. What is a pixel?
7. In what bias condition is a photodiode normally operated?
8. When the intensity of the incident light (irradiance) on a photodiode increases, what happens to its internal reverse resistance?
9. What is *dark current*?

3–5 OTHER TYPES OF DIODES

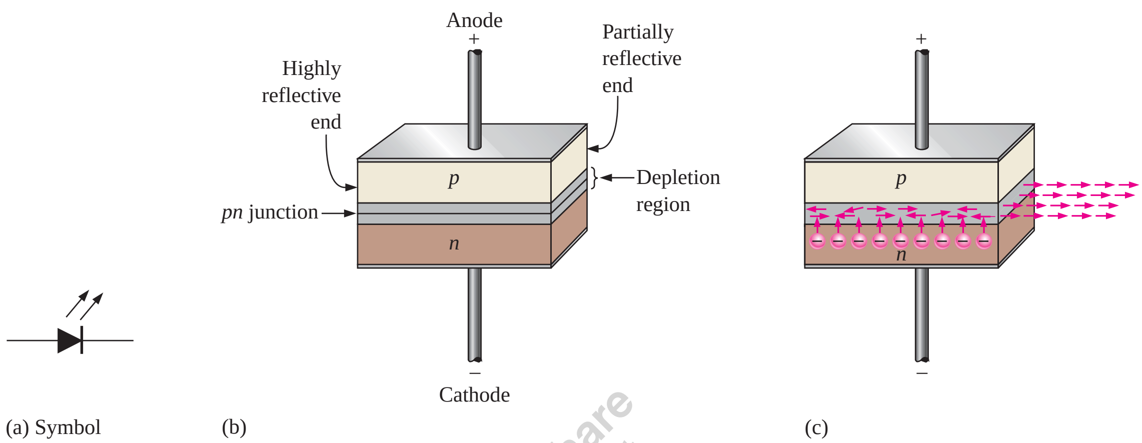
In this section, several types of diodes that you are less likely to encounter as a technician but are nevertheless important are introduced. Among these are the laser diode, the Schottky diode, the *pin* diode, the step-recovery diode, the tunnel diode, and the current regulator diode.

After completing this section, you should be able to

- **Discuss the basic characteristics of several types of diodes**
- Discuss the laser diode and an application
  - Identify the schematic symbol
- Discuss the Schottky diode
  - Identify the schematic symbol
- Discuss the *pin* diode
- Discuss the step-recovery diode
  - Identify the schematic symbol
- Discuss the tunnel diode
  - Identify the schematic symbol ◆ Describe a tunnel diode application
- Discuss the current regulation diode
  - Identify the schematic symbol

The Laser Diode

The term **laser** stands for *l*ight *a*mplification by *s*timulated *e*mission of *r*adiation. Laser light is **monochromatic,** which means that it consists of a single color and not a mixture of colors. Laser light is also called **coherent light,** a single wavelength, as compared to incoherent light, which consists of a wide band of wavelengths. The laser diode normally emits coherent light, whereas the LED emits incoherent light. The symbols are the same as shown in Figure 3–48(a).



▲ FIGURE 3–48

Basic laser diode construction and operation.

The basic construction of a laser diode is shown in Figure 3–48(b). A *pn* junction is formed by two layers of doped gallium arsenide. The length of the *pn* junction bears a precise relationship with the wavelength of the light to be emitted. There is a highly reflective surface at one end of the *pn* junction and a partially reflective surface at the other end, forming a resonant cavity for the photons. External leads provide the anode and cathode connections.

The basic operation is as follows. The laser diode is forward-biased by an external voltage source. As electrons move through the junction, recombination occurs just as in an ordinary diode. As electrons fall into holes to recombine, photons are released. A released photon can strike an atom, causing another photon to be released. As the forward current is increased, more electrons enter the depletion region and cause more photons to be emitted. Eventually some of the photons that are randomly drifting within the depletion region strike the reflected surfaces perpendicularly. These reflected photons move along the depletion region, striking atoms and releasing additional photons due to the avalanche effect. This back-and-forth movement of photons increases as the generation of photons "snowballs" until a very intense beam of laser light is formed by the photons that pass through the partially reflective end of the *pn* junction.

Each photon produced in this process is identical to the other photons in energy level, phase relationship, and frequency. So a single wavelength of intense light emerges from the laser diode, as indicated in Figure 3–48(c). Laser diodes have a threshold level of current above which the laser action occurs and below which the diode behaves essentially as an LED, emitting incoherent light.

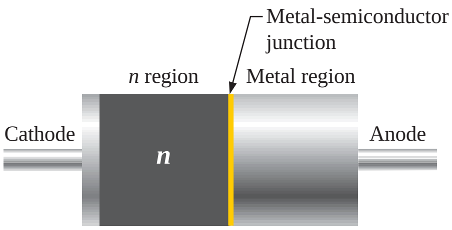
An Application Laser diodes and photodiodes are used in the pick-up system of compact disk (CD) players. Audio information (sound) is digitally recorded in stereo on the surface of a compact disk in the form of microscopic "pits" and "flats." A lens arrangement focuses the laser beam from the diode onto the CD surface. As the CD rotates, the lens and beam follow the track under control of a servomotor. The laser light, which is altered by the pits and flats along the recorded track, is reflected back from the track through a lens and optical system to infrared photodiodes. The signal from the photodiodes is then used to reproduce the digitally recorded sound. Laser diodes are also used in laser printers and fiber-optic systems.

The Schottky Diode

Schottky diodes are high-current diodes used primarily in high-frequency and fast-switching applications. They are also known as *hot-carrier diodes*. The term *hot-carrier* is derived from the higher energy level of electrons in the *n* region compared to those in the metal region. A Schottky diode symbol is shown in Figure 3–49. A Schottky diode is formed by joining a doped semiconductor region (usually *n*-type) with a metal such as gold, silver, or platinum. Rather than a *pn* junction, there is a metal-to-semiconductor junction, as shown in Figure 3–50. The forward voltage drop is typically around 0.3 V because there is no depletion region as in a *pn* junction diode.

▲ **FIGURE 3–49**

Schottky diode symbol.



◀ **FIGURE 3–50**

Basic internal construction of a Schottky diode.

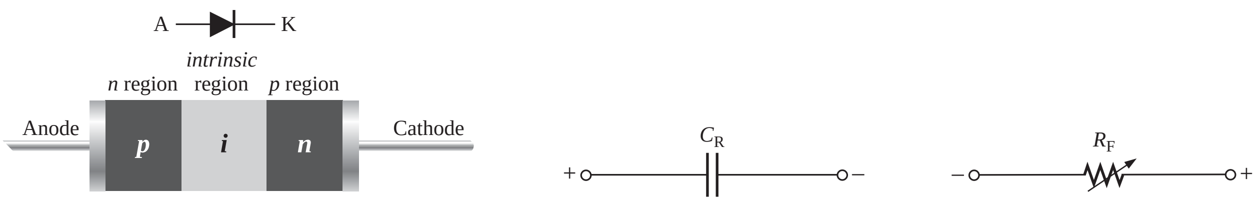
The Schottky diode operates only with majority carriers. There are no minority carriers and thus no reverse leakage current as in other types of diodes. The metal region is heavily occupied with conduction-band electrons, and the *n*-type semiconductor region is lightly doped. When forward-biased, the higher energy electrons in the *n* region are injected into the metal region where they give up their excess energy very rapidly. Since there are no minority carriers, as in a conventional rectifier diode, there is a very rapid response to a change in bias. The Schottky is a fast-switching diode, and most of its applications make use of this property. It can be used in high-frequency applications and in many digital circuits to decrease switching times. The LS family of TTL logic (LS stands for low-power Schottky) is one type of digital integrated circuit that uses the Schottky diode.

GREENTECH NOTE

Thin-film PV solar panels, a relatively new development, use a somewhat different concept for the diodes than a standard crystalline silicon panel uses. The thin films are based on amorphous silicon, rather than crystalline silicon, as standard PV panels are. The *p* and *n* layers are separated by an intrinsic layer forming a *p-i-n* diode. Because they are very thin, light can penetrate the entire layer and multiple layers can be added with different band gaps to capture a larger percentage of the light spectrum. This is a promising method for forming large flexible panels.

The *PIN* Diode

The *pin* diode consists of heavily doped *p* and *n* regions separated by an intrinsic (*i*) region, as shown in Figure 3–51(a). When reverse-biased, the *pin* diode acts like a nearly constant capacitance. When forward-biased, it acts like a current-controlled variable resistance. This is shown in Figure 3–51(b) and (c). The low forward resistance of the intrinsic region decreases with increasing current.



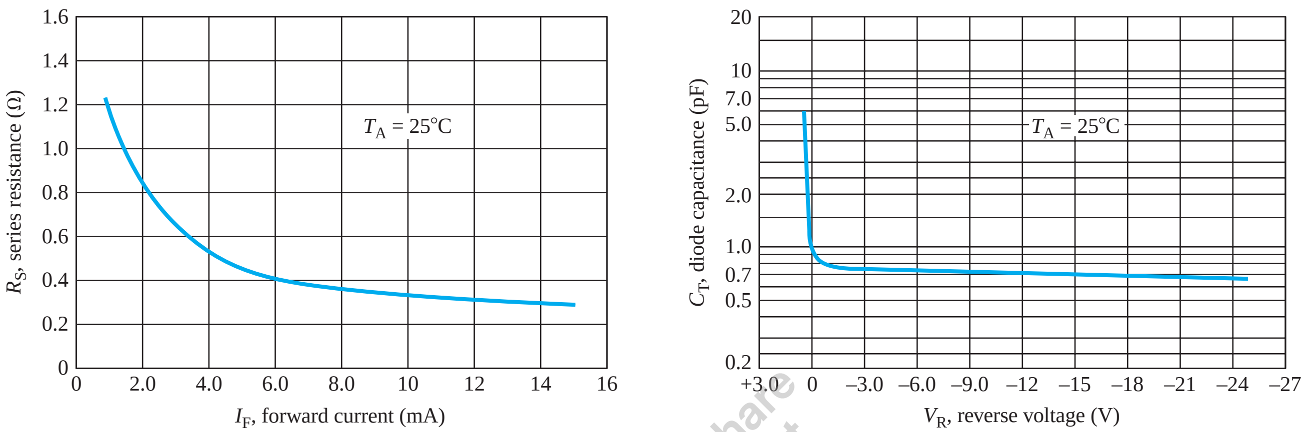
(a) Construction (b) Reverse-biased (c) Forward-biased

▲ **FIGURE 3–51**

PIN diode.

The forward series resistance characteristic and the reverse capacitance characteristic are shown graphically in Figure 3–52 for a typical *pin* diode.

The *pin* diode is used as a dc-controlled microwave switch operated by rapid changes in bias or as a modulating device that takes advantage of the variable forward-resistance characteristic. Since no rectification occurs at the *pn* junction, a high-frequency signal can be modulated (varied) by a lower-frequency bias variation. A *pin* diode can also be used in attenuator applications because its resistance can be controlled by the amount of current. Certain types of *pin* diodes are used as photodetectors in fiber-optic systems.



▲ **FIGURE 3–52**

PIN diode characteristics.

The Step-Recovery Diode

The step-recovery diode uses graded doping where the doping level of the semiconductive materials is reduced as the *pn* junction is approached. This produces an abrupt turn-off time by allowing a fast release of stored charge when switching from forward to reverse bias. It also allows a rapid re-establishment of forward current when switching from reverse to forward bias. This diode is used in very high frequency (VHF) and fast-switching applications.

HISTORY NOTE

Leo Esaki won the Nobel Prize in physics in 1973 for the invention of the tunnel diode in the late 1950s. Surprisingly, in 1976 Robert Noyce, cofounder of Intel Corp., revealed in a talk before the MIT Club of New York that he had in his notebooks from 1956 a complete description of the tunnel diode. However, credit for the invention is given to Esaki and the tunnel diode is also known as the Esaki diode in his honor.

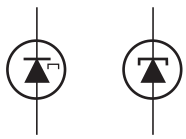
The Tunnel Diode

The tunnel diode exhibits a special characteristic known as *negative resistance.* This feature makes it useful in oscillator and microwave amplifier applications. Two alternate symbols are shown in Figure 3–53. Tunnel diodes are constructed with germanium or gallium arsenide by doping the *p* and *n* regions much more heavily than in a conventional rectifier diode. This heavy doping results in an extremely narrow depletion region. The heavy doping allows conduction for all reverse voltages so that there is no breakdown effect as with the conventional rectifier diode. This is shown in Figure 3–54.

Also, the extremely narrow depletion region permits electrons to “tunnel” through the *pn* junction at very low forward-bias voltages, and the diode acts as a conductor. This is shown in Figure 3–54 between points *A* and *B*. At point *B*, the forward voltage begins to develop a barrier, and the current begins to decrease as the forward voltage continues to increase. This is the *negative-resistance region.*

$$R_F = \frac{\Delta V_F}{\Delta I_F}$$

This effect is opposite to that described in Ohm’s law, where an increase in voltage results in an increase in current. At point *C*, the diode begins to act as a conventional forward-biased diode.



▲ **FIGURE 3–53**

Tunnel diode symbols.

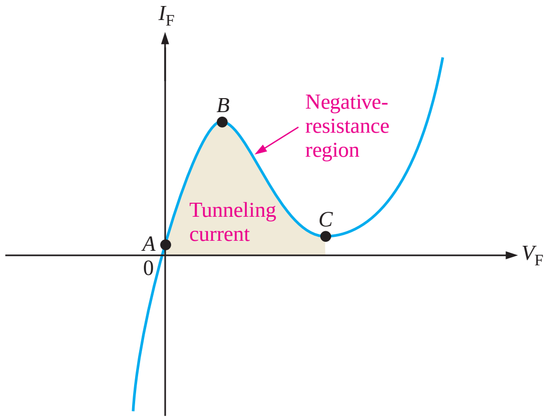


FIGURE 3–54

Tunnel diode characteristic curve.

An Application A parallel resonant circuit can be represented by a capacitance, inductance, and resistance in parallel, as in Figure 3–55(a). R_P is the parallel equivalent of the series winding resistance of the coil. When the tank circuit is "shocked" into oscillation by an application of voltage as in Figure 3–55(b), a damped sinusoidal output results. The damping is due to the resistance of the tank, which prevents a sustained oscillation because energy is lost when there is current through the resistance.

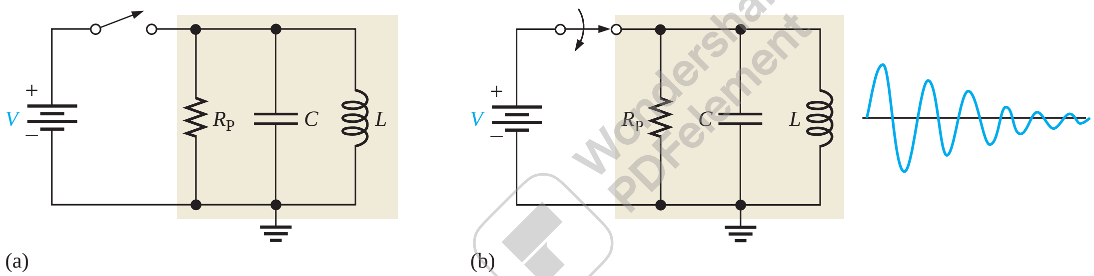


FIGURE 3–55

Parallel resonant circuit.

If a tunnel diode is placed in series with the tank circuit and biased at the center of the negative-resistance portion of its characteristic curve, as shown in Figure 3–56, a sustained oscillation (constant sinusoidal voltage) will result on the output. This is because the negative-resistance characteristic of the tunnel diode counteracts the positive-resistance characteristic of the tank resistance. The tunnel diode is only used at very high frequencies.

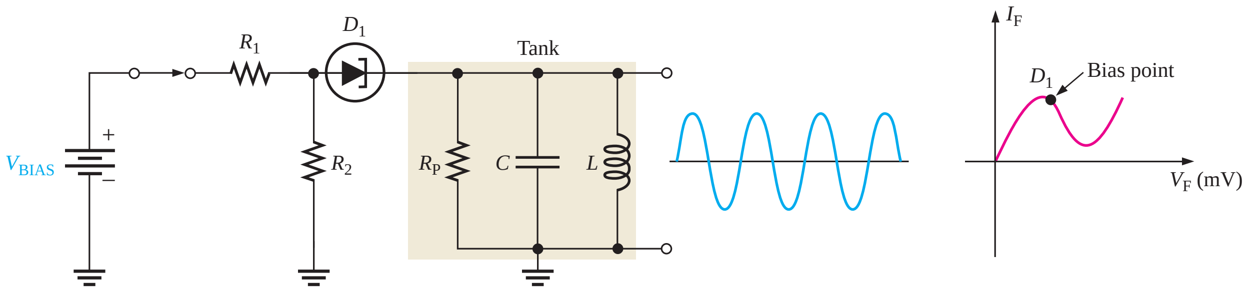


FIGURE 3–56

Basic tunnel diode oscillator.

Current Regulator Diode

The current regulator diode is often referred to as a constant-current diode. Rather than maintaining a constant voltage, as the zener diode does, this diode maintains a constant current. The symbol is shown in Figure 3–57.

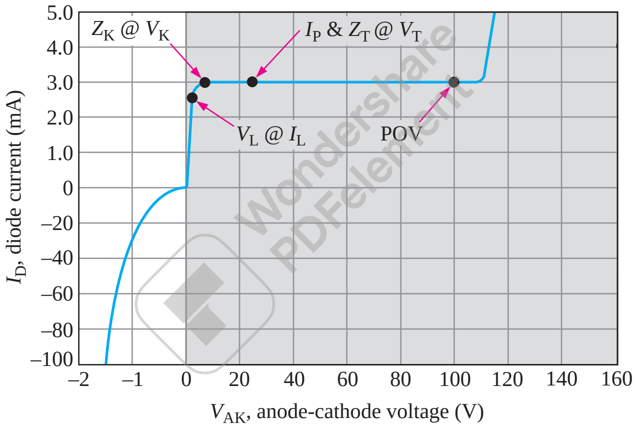
FIGURE 3–57

Symbol for a current regulator diode.

Figure 3–58 shows a typical characteristic curve. The current regulator diode operates in forward bias (shaded region), and the forward current becomes a specified constant value at forward voltages ranging from about 1.5 V to about 6 V, depending on the diode type. The constant forward current is called the *regulator current* and is designated I_P. For example, the 1N5283–1N5314 series of diodes have nominal regulator currents ranging from 220 μA to 4.7 mA. These diodes may be used in parallel to obtain higher currents. This diode does not have a sharply defined reverse breakdown, so the reverse current begins to increase for V_{AK} values of less than 0 V (unshaded region of the figure). This device should never be operated in reverse bias.

FIGURE 3–58

Typical characteristic curve for a current regulator diode.



In forward bias, the diode regulation begins at the limiting voltage, V_L, and extends up to the POV (peak operating voltage). Notice that between V_K and POV, the current is essentially constant. V_T is the test voltage at which I_P and the diode impedance, Z_T, are specified on a datasheet. The impedance Z_T has very high values ranging from 235 kΩ to 25 MΩ for the diode series mentioned before.

SECTION 3–5 CHECKUP

1. What does *laser* mean?
2. What is the difference between incoherent and coherent light and which is produced by a laser diode?
3. What are the primary application areas for Schottky diodes?
4. What is a hot-carrier diode?
5. What is the key characteristic of a tunnel diode?
6. What is one application for a tunnel diode?
7. Name the three regions of a *pin* diode.
8. Between what two voltages does a current regulator diode operate?

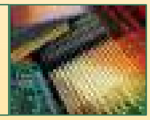
3–6 TROUBLESHOOTING

In this section, you will see how a faulty zener diode can affect the output of a regulated dc power supply. Although IC regulators are generally used for power supply outputs, the zener is occasionally used when less precise regulation and low current is acceptable. Like other diodes, the zener can fail open, it can exhibit degraded performance, or it can short out.

After completing this section, you should be able to

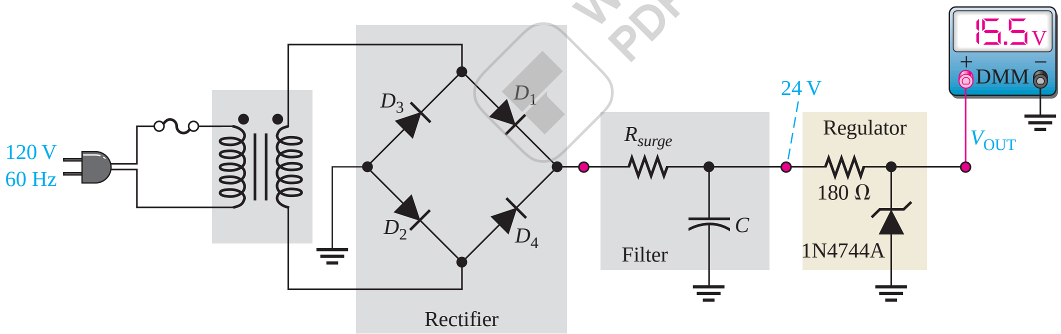
- **Troubleshoot zener diode regulators**
  - Recognize the effects of an open zener
  - Recognize the effects of a zener with degraded performance or shorted

Chapter 18: Basic Programming Concepts for Automated Testing
Selected sections from Chapter 18 may be introduced as part of this troubleshooting coverage or, optionally, the entire Chapter 18 may be covered later or not at all.

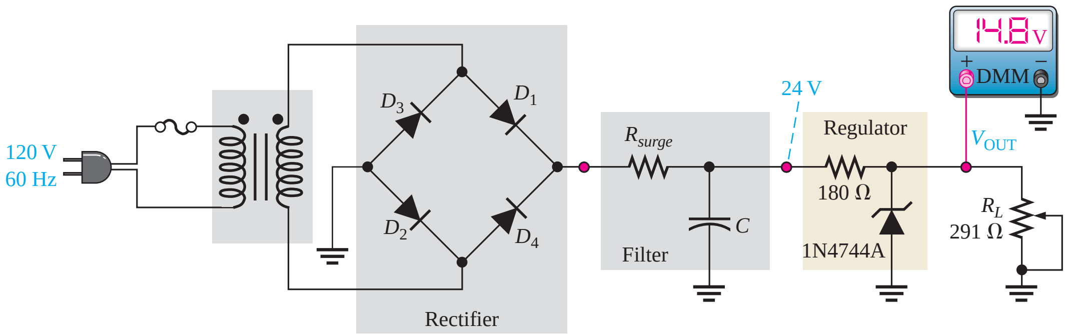


A Zener-Regulated DC Power Supply

Figure 3–59 shows a filtered dc power supply that produces a constant 24 V before it is regulated down to 15 V by the zener regulator. The 1N4744A zener diode is the same as the one in Example 3–7. A no-load check of the regulated output voltage shows 15.5 V as indicated in part (a). The typical voltage expected at the zener test current for this particular



(a) Correct output voltage with no load



(b) Correct output voltage with full load

▲ FIGURE 3–59

Zener-regulated power supply test.

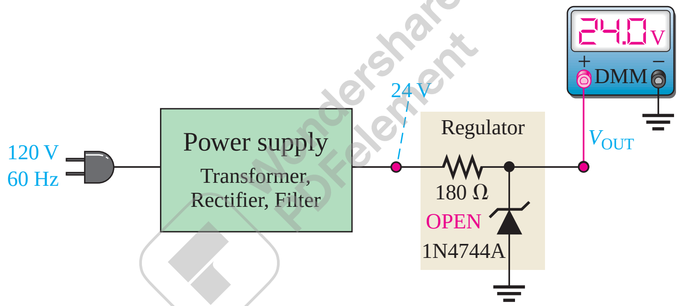
diode is 15 V. In part (b), a potentiometer is connected to provide a variable load resistance. It is adjusted to a minimum value for a full-load test as determined by the following calculations. The full-load test is at minimum zener current (I_{ZK}). The meter reading of 14.8 V indicates approximately the expected output voltage of 15.0 V.

$$I_T = \frac{24\text{ V} - 14.8\text{ V}}{180\ \Omega} = 51.1\text{ mA}$$

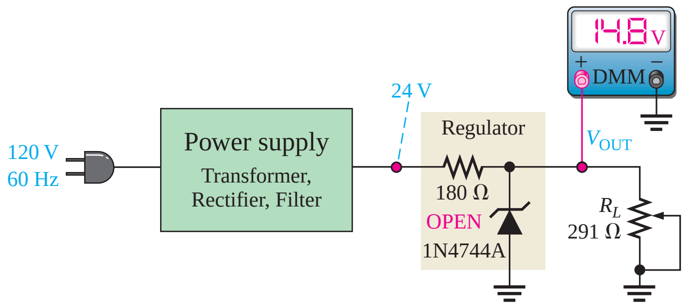
$$I_L = I_T - I_Z = 51.1\text{ mA} - 0.25\text{ mA} = 50.9\text{ mA}$$

$$R_{L(min)} = \frac{14.8\text{ V}}{50.9\text{ mA}} = 291\ \Omega$$

Case 1: Zener Diode Open If the zener diode fails open, the power supply test gives the approximate results indicated in Figure 3–60. In the no-load check shown in part (a), the output voltage is 24 V because there is no voltage dropped between the filtered output of the power supply and the output terminal. This definitely indicates an open between the output terminal and ground. In the full-load check, the voltage of 14.8 V results from the voltage-divider action of the 180 Ω series resistor and the 291 Ω load. In this case, the result is too close to the normal reading to be a reliable fault indication but the no-load check will verify the problem. Also, if R_L is varied, V_{OUT} will vary if the zener diode is open.



(a) Open zener diode with no load

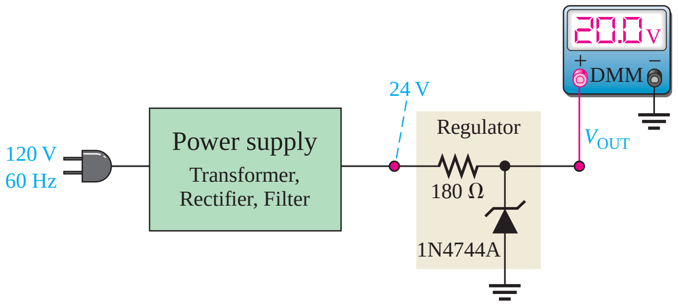


(b) Open zener diode cannot be detected by full-load measurement in this case.

▲ **FIGURE 3–60**

Indications of an open zener.

Case 2: Incorrect Zener Voltage As indicated in Figure 3–61, a no-load check that results in an output voltage greater than the maximum zener voltage but less than the power supply output voltage indicates that the zener has failed such that its internal impedance is more than it should be. The 20 V output in this case is 4.5 V higher than the expected value of 15.5 V. That additional voltage indicates the zener is faulty or the wrong type has been installed. A 0 V output, of course, indicates that there is a short.



▲ **FIGURE 3–61**

Indication of faulty or wrong zener.

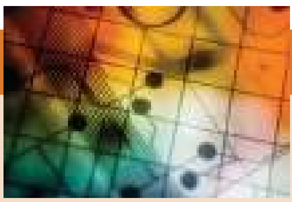
Multisim Troubleshooting Exercises

These file circuits are in the Troubleshooting Exercises folder on the companion website. Open each file and determine if the circuit is working properly. If it is not working properly, determine the fault.

1. Multisim file TSE03-01
2. Multisim file TSE03-02
3. Multisim file TSE03-03
4. Multisim file TSE03-04
5. Multisim file TSE03-05

SECTION 3–6 CHECKUP

1. In a zener regulator, what are the symptoms of an open zener diode?
2. If a zener regulator fails so that the zener impedance is greater than the specified value, is the output voltage more or less than it should be?
3. If you measure 0 V at the output of a zener-regulated power supply, what is the most likely fault(s)?
4. The zener diode regulator in a power supply is open. What will you observe on the output with a voltmeter if the load resistance is varied within its specified range?



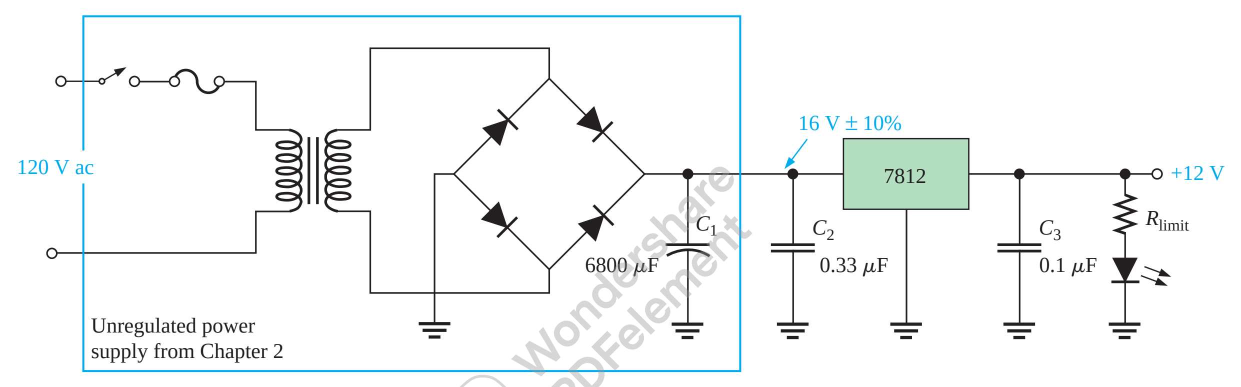
Application Activity: *Regulated DC Power Supply*

The unregulated 16 V dc power supply developed in Chapter 2 is to be upgraded to a regulated power supply with a fixed output voltage of 12 V. An integrated circuit 3–terminal voltage regulator is to be used and a red LED incorporated to indicate when the power is on. The printed circuit board for the unregulated power supply was designed to accommodate these additions.

The Circuit

Practical considerations for the circuit are the type of regulator, the selection of the LED power-on indicator and limiting resistor, and the value and placement of the fuse.

The Regulator The 78XX series of linear voltage regulators provide positive fixed output voltages for a range of values. The last two digits in the part number indicate the output voltage. The 7812 provides a 12 V regulated output. The change in output voltage for a specified change in input voltage is called the *line regulation.* The change in output voltage for a specified change in load current is called the *load regulation.* These parameters are specified on the datasheet. It is recommended by the manufacturer that a 0.33 μF capacitor be connected from the input terminal to ground and a 0.1 μF connected from the output terminal to ground, as shown in Figure 3–62 to prevent high-frequency oscillations and improve the performance. You may wonder about putting a small-value capacitor in parallel with a large one; the reason is that the large filter capacitor has an internal equivalent series resistance, which affects the high frequency response of the system. The effect is cancelled with the small capacitor.



▲ FIGURE 3–62

12 V regulated power supply.

A partial datasheet for a 7812 is shown in Figure 3–63(a) Notice that there is a range of nominal output voltages, but it is typically 12 V. The line and load regulation specify how much the output can vary about the nominal output value. For example, the typical 12 V output will change no more than 11 mV (typical) as the load current changes from 5 mA to 1. 5 A. Package configurations are shown in part (b).

1. From the datasheet, determine the maximum output voltage if the input voltage to the regulator increases to 22 V, assuming a nominal output of 12 V.
2. From the datasheet, determine how much the typical output voltage changes when the load current changes from 250 mA to 750 mA.

The LED A typical partial datasheet for a visible red LED is shown in Figure 3–64. As the datasheet shows, a forward current of 10 mA to 20 mA is used for the test data.

3. Determine the value of the resistor shown in Figure 3–62 for limiting the LED current to 20 mA and use the next higher standard value. Also specify the power rating of the limiting resistor.

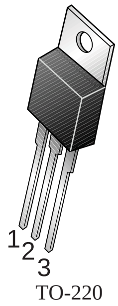
The Fuse The fuse will be in series with the primary winding of the transformer, as shown in Figure 3–62. The fuse should be calculated based on the maximum allowable primary current. Recall from your dc/ac circuits course that if the voltage is stepped

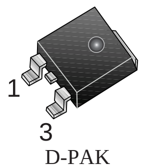
Electrical Characteristics (MC7812E)

(Refer to test circuit ,0°C < T_J < 125°C, I_O = 500mA, V_I =19V, C_I= 0.33µF, C_O=0.1µF, unless otherwise specified)

Parameter	Symbol	Conditions		MC7812E Min.	Typ.	Max.	Unit
Output Voltage	V_O	T_J = +25°C		11.5	12	12.5	V
		5.0mA ≤ I_O ≤ 1.0A, P_O ≤ 15W V_I = 14.5V to 27V		11.4	12	12.6	
Line Regulation (Note1)	Regline	T_J = +25°C	V_I = 14.5V to 30V	-	10	240	mV
			V_I = 16V to 22V	-	3.0	120	
Load Regulation (Note1)	Regload	T_J = +25°C	I_O = 5mA to 1.5A	-	11	240	mV
			I_O = 250mA to 750mA	-	5.0	120	
Quiescent Current	I_Q	T_J = +25°C		-	5.1	8.0	mA
Quiescent Current Change	ΔI_Q	I_O = 5mA to 1.0A		-	0.1	0.5	mA
		V_I = 14.5V to 30V		-	0.5	1.0	
Output Voltage Drift (Note2)	$\Delta V_O/\Delta T$	I_O = 5mA		-	-1	-	mV/°C
Output Noise Voltage	V_N	f = 10Hz to 100kHz, TA = +25 °C		-	76	-	µV/Vo
Ripple Rejection (Note2)	RR	f = 120Hz V_I = 15V to 25V		55	71	-	dB
Dropout Voltage	V_{Drop}	I_O = 1A, T_J = +25°C		-	2	-	V
Output Resistance (Note2)	r_O	f = 1kHz		-	18	-	mΩ
Short Circuit Current	I_{SC}	V_I = 35V, T_A= +25°C		-	230	-	mA
Peak Current (Note2)	I_{PK}	T_J = +25°C		-	2.2	-	A

(a)





(b) 1—input, 2—ground, 3—output

▲ **FIGURE 3–63**

Partial datasheet and packages for a 7812 regulator. You can view an entire datasheet at *www.fairchildsemiconductor.com*. Copyright Fairchild Semiconductor Corporation. Used by permission.

Optical and Electrical Characteristics

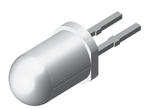
T_{amb} = 25 °C, unless otherwise specified

Red

TLHK51..

Parameter	Test condition	Part	Symbol	Min	Typ.	Max	Unit
Luminous intensity [1)]	I_F = 20 mA	TLHK5100	I_V	320			mcd
Dominant wavelength	I_F = 10 mA		λ_d	626	630	639	nm
Peak wavelength	I_F = 10 mA		λ_p		643		nm
Angle of half intensity	I_F = 10 mA		φ		± 9		deg
Forward voltage	I_F = 20 mA		V_F		1.9	2.6	V
Reverse voltage	I_R = 10 µA		V_R	5			V
Junction capacitance	V_R = 0, f = 1 MHz		C_j		15		pF

[1)] in one Packing Unit $I_{Vmin}/I_{Vmax} \leq 0.5$

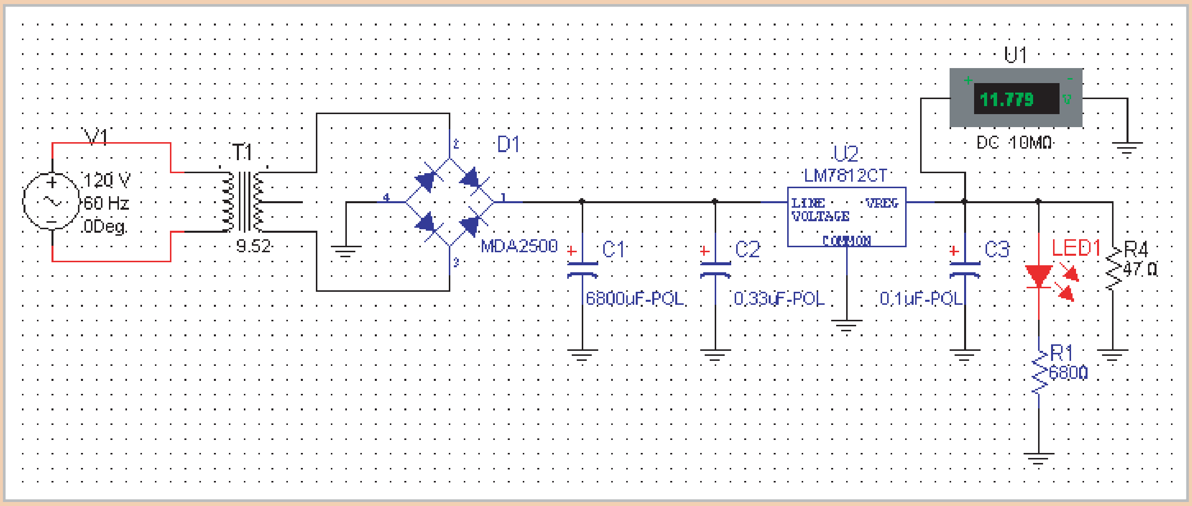


▲ **FIGURE 3–64**

Partial datasheet and package for a typical red LED. To view a complete datasheet, go to *www. vishay.com*. Datasheet courtesy of Vishay Intertechnology, Inc.

down, the current is stepped up. From the specifications for the unregulated power supply, the maximum load current is 250 mA. The current required for the power-on LED indicator is 15 mA. So, the total secondary current is 265 mA. The primary current will be the secondary current divided by the turns ratio.

4. Calculate the primary current and use this value to select a fuse rating.



▲ FIGURE 3–65

Simulation of the regulated 12 V power supply circuit.

Simulation

In the development of a new circuit, it is helpful to simulate the circuit using a software program before actually building it and committing it to hardware. We will use Multisim to simulate this power supply circuit. Figure 3–65 shows the simulated regulated power supply circuit. The unregulated power supply was previously tested, so you need only to verify that the regulated output is correct. A load resistor value is chosen to draw a current equal to or greater than the specified maximum load current.

$$R_L = \frac{12\text{ V}}{250\text{ mA}} = 48\ \Omega$$

The closest standard value is 47 Ω, which draws 255 mA at 12 V.

5. Determine the power rating for the load resistor.

Simulate the circuit using your Multisim software. Verify the operation with the virtual voltmeter.

Prototyping and Testing

Now that all the components have been selected and the circuit has been simulated, the new components are added to the power supply protoboard from Experiment 2 and the circuit is tested.

Lab Experiment

To build and test a similar circuit, go to Experiment 3 in your lab manual (*Laboratory Exercises for Electronic Devices* by David Buchla and Steven Wetterling).

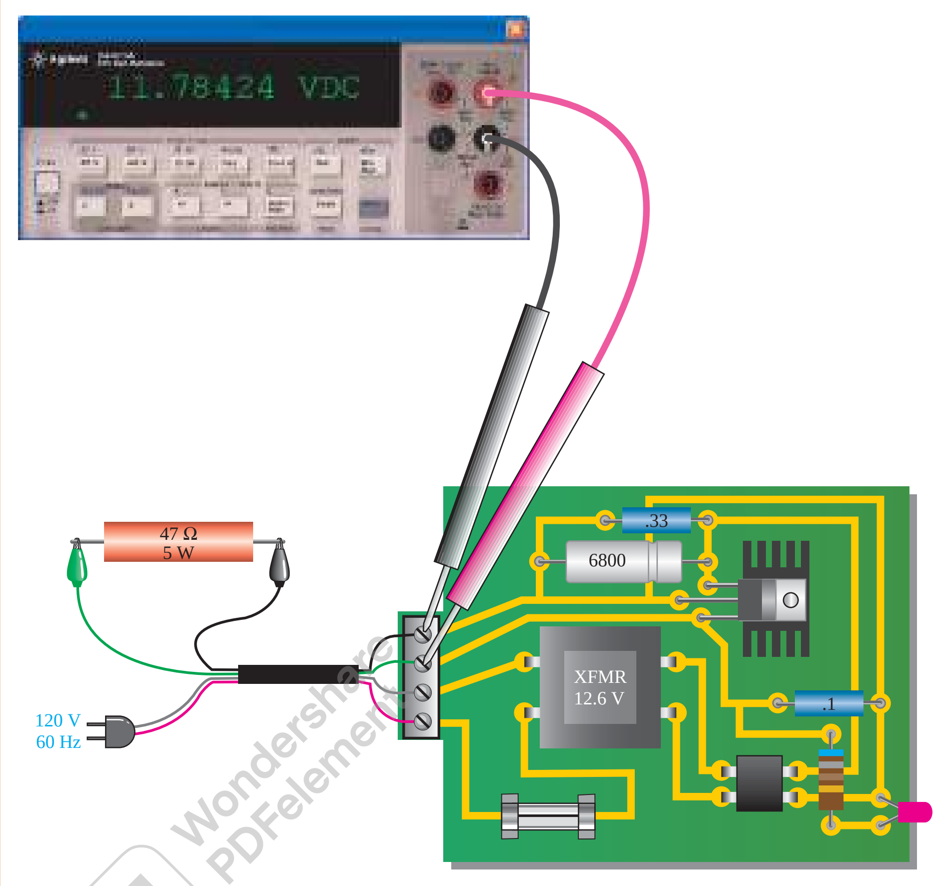
Printed Circuit Board

The 12 V regulated power supply prototype has been built and tested. It is now committed to a printed circuit layout, as shown in Figure 3–66. Notice that a heat sink is used with the regulator IC to increase its ability to dissipate power. With the ac line voltage and load resistor connected, the output voltage is measured.

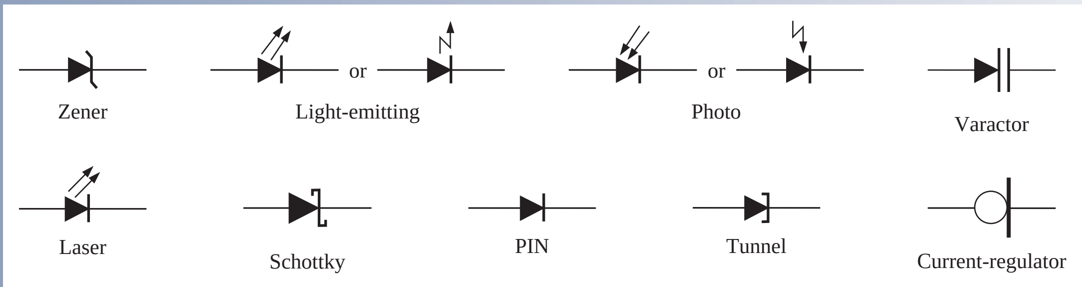
6. Compare the printed circuit board to the schematic in Figure 3–65.
7. Calculate the power dissipated by the regulator for an output of 12 V.

FIGURE 3–66

Regulated 12 V power supply on the printed circuit (PC) board.



SUMMARY OF DIODE SYMBOLS



SUMMARY

Section 3–1

- The zener diode operates in reverse breakdown.
- There are two breakdown mechanisms in a zener diode: avalanche breakdown and zener breakdown.
- When $V_Z < 5$ V, zener breakdown is predominant.

- When $V_Z > 5$ V, avalanche breakdown is predominant.
- A zener diode maintains a nearly constant voltage across its terminals over a specified range of zener currents.
- Zener diodes are available in many voltage ratings ranging from less than 1 V to more than 250 V.

Section 3–2

- Zener diodes are used as voltage references, regulators, and limiters.

Section 3–3

- A varactor diode acts as a variable capacitor under reverse-bias conditions.
- The capacitance of a varactor varies inversely with reverse-bias voltage.
- The current regulator diode keeps its forward current at a constant specified value.

Section 3–4

- An LED emits light when forward-biased.
- LEDs are available for either infrared or visible light.
- High-intensity LEDs are used in large-screen displays, traffic lights, automotive lighting, and home lighting.
- An organic LED (OLED) uses two or three layers of organic material to produce light.
- Quantum dots are semiconductor devices that emit light when energized from an external source.
- The photodiode exhibits an increase in reverse current with light intensity.

Section 3–5

- The Schottky diode has a metal-to-semiconductor junction. It is used in fast-switching applications.
- The tunnel diode is used in oscillator circuits.
- The *pin* diode has a *p* region, an *n* region, and an intrinsic (*i*) region and displays a variable resistance characteristic when forward-biased and a constant capacitance when reverse-biased.
- A laser diode is similar to an LED except that it emits coherent (single wavelength) light when the forward current exceeds a threshold value.

KEY TERMS

Key terms and other bold terms in the chapter are defined in the end-of-book glossary.

Electroluminescence The process of releasing light energy by the recombination of electrons in a semiconductor.

Laser *L*ight *a*mplification by *s*timulated *e*mission of *r*adiation.

Light-emitting diode (LED) A type of diode that emits light when there is forward current.

Photodiode A diode in which the reverse current varies directly with the amount of light.

Pixel In an LED display screen, the basic unit for producing colored light and consisting of red, green, and blue LEDs.

Varactor A variable capacitance diode.

Zener breakdown The lower voltage breakdown in a zener diode.

Zener diode A diode designed for limiting the voltage across its terminals in reverse bias.

KEY FORMULAS

3–1	$Z_Z = \dfrac{\Delta V_Z}{\Delta I_Z}$	Zener impedance
3–2	$\Delta V_Z = V_Z \times TC \times \Delta T$	V_Z temperature change when TC is %/°C
3–3	$\Delta V_Z = TC \times \Delta T$	V_Z temperature change when TC is mV/°C

TRUE/FALSE QUIZ

Answers can be found at www.pearsonhighered.com/floyd.

1. The zener diode normally operates in reverse breakdown.
2. A zener diode can be used as a voltage regulator.
3. There is no current when a zener is in reverse breakdown.
4. The varactor diode normally operates in forward bias.
5. The varactor diode is used as a variable capacitor.
6. The capacitance of a varactor varies directly with reverse voltage.
7. The LED is based on the process of electroluminescence.
8. The LED is normally operated in forward bias.
9. OLED stands for operational light-emitting diode.
10. The photodiode operates in reverse bias.
11. The reverse current of a photodiode increases as the incident light increases.
12. The light emitted by a laser diode is monochromatic.

CIRCUIT-ACTION QUIZ

Answers can be found at www.pearsonhighered.com/floyd.

1. If the input voltage in Figure 3–11 is increased from 5 V to 10 V, ideally the output voltage will
   (a) increase **(b)** decrease **(c)** not change
2. If the input voltage in Figure 3–14 is reduced by 2 V, the zener current will
   (a) increase **(b)** decrease **(c)** not change
3. If R_L in Figure 3–14 is removed, the current through the zener diode will
   (a) increase **(b)** decrease **(c)** not change
4. If the zener opens in Figure 3–14, the output voltage will
   (a) increase **(b)** decrease **(c)** not change
5. If R in Figure 3–14 is increased, the current to the load resistor will
   (a) increase **(b)** decrease **(c)** not change
6. If the input voltage amplitude in Figure 3–18(a) is increased, the positive output voltage will
   (a) increase **(b)** decrease **(c)** not change
7. If the input voltage amplitude in Figure 3–19(a) is reduced, the amplitude of the output voltage will
   (a) increase **(b)** decrease **(c)** not change
8. If the varactor capacitance is increased in Figure 3–26, the resonant frequency will
   (a) increase **(b)** decrease **(c)** not change
9. If the reverse voltage across the varactor in Figure 3–26 is increased, the frequency will
   (a) increase **(b)** decrease **(c)** not change
10. If the bias voltage in Figure 3–30 is increased, the light output of the LED will
    (a) increase **(b)** decrease **(c)** not change
11. If the bias voltage in Figure 3–30 is reversed, the light output of the LED will
    (a) increase **(b)** decrease **(c)** not change

SELF-TEST

Answers can be found at www.pearsonhighered.com/floyd.

Section 3–1

1. The cathode of a zener diode in a voltage regulator is normally
   (a) more positive than the anode **(b)** more negative than the anode
   (c) at +0.7 V **(d)** grounded

2. If a certain zener diode has a zener voltage of 3.6 V, it operates in
(a) regulated breakdown **(b)** zener breakdown
(c) forward conduction **(d)** avalanche breakdown

3. For a certain 12 V zener diode, a 10 mA change in zener current produces a 0.1 V change in zener voltage. The zener impedance for this current range is
(a) 1 Ω **(b)** 100 Ω **(c)** 10 Ω **(d)** 0.1 Ω

4. The datasheet for a particular zener gives $V_Z = 10$ V at $I_Z = 500$ mA. Z_Z for these conditions is
(a) 50 Ω **(b)** 20 Ω **(c)** 10 Ω **(d)** unknown

Section 3–2

5. A no-load condition means that
(a) the load has infinite resistance **(b)** the load has zero resistance
(c) the output terminals are open **(d)** answers(a) and (c)

Section 3–3

6. A varactor diode exhibits
(a) a variable capacitance that depends on reverse voltage
(b) a variable resistance that depends on reverse voltage
(c) a variable capacitance that depends on forward current
(d) a constant capacitance over a range of reverse voltages

Section 3–4

7. An LED
(a) emits light when reverse-biased **(b)** senses light when reverse-biased
(c) emits light when forward-biased **(d)** acts as a variable resistance

8. Compared to a visible red LED, an infrared LED
(a) produces light with shorter wavelengths **(b)** produces light of all wavelengths
(c) produces only one color of light **(d)** produces light with longer wavelengths

9. Compared to incandescent bulbs, high-intensity LEDs
(a) are brighter **(b)** have a much longer life
(c) use less power **(d)** all of the above

10. An OLED differs from a conventional LED in that it
(a) requires no bias voltage
(b) has layers of organic material in the place of a *pn* junction
(c) can be implemented using an inkjet printing process
(d) both (b) and (c)

11. An infrared LED is optically coupled to a photodiode. When the LED is turned off, the reading on an ammeter in series with the reverse-biased photodiode will
(a) not change **(b)** decrease
(c) increase **(d)** fluctuate

12. The internal resistance of a photodiode
(a) increases with light intensity when reverse-biased
(b) decreases with light intensity when reverse-biased
(c) increases with light intensity when forward-biased
(d) decreases with light intensity when forward-biased

Section 3–5

13. A laser diode produces
(a) incoherent light **(b)** coherent light
(c) monochromatic light **(d)** both (b) and (c)

14. A diode that has a negative resistance characteristic is the
(a) Schottky diode **(b)** tunnel diode **(c)** laser diode **(d)** hot-carrier diode

15. In order for a system to function properly, the various types of circuits that make up the system must be
(a) properly biased **(b)** properly connected **(c)** properly interfaced
(d) all of the above **(e)** answers(a) and (b)

PROBLEMS

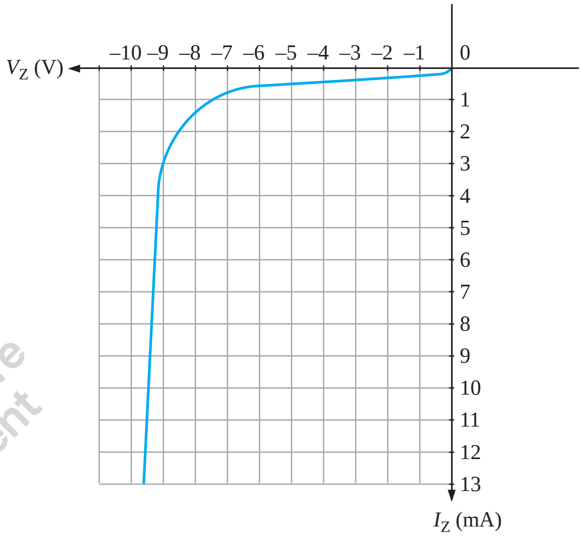
Answers to all odd-numbered problems are at the end of the book.

BASIC PROBLEMS

Section 3–1 The Zener Diode

1. A certain zener diode has a $V_Z = 7.5$ V and an $Z_Z = 5\ \Omega$ at a certain current. Draw the equivalent circuit.
2. From the characteristic curve in Figure 3–67, what is the approximate minimum zener current (I_{ZK}) and the approximate zener voltage at I_{ZK}?

▶ FIGURE 3–67

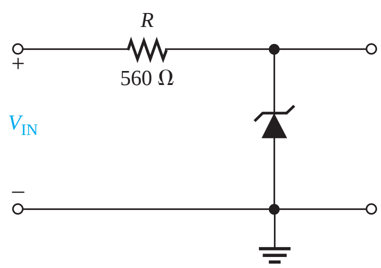


3. When the reverse current in a particular zener diode increases from 20 mA to 30 mA, the zener voltage changes from 5.6 V to 5.65 V. What is the impedance of this device?
4. A zener has an impedance of 15 Ω. What is its terminal voltage at 50 mA if $V_Z = 4.7$ V at $I_Z = 25$ mA?
5. A certain zener diode has the following specifications: $V_Z = 6.8$ V at 25°C and $TC = +0.04\%/°C$. Determine the zener voltage at 70°C.

Section 3–2 Zener Diode Applications

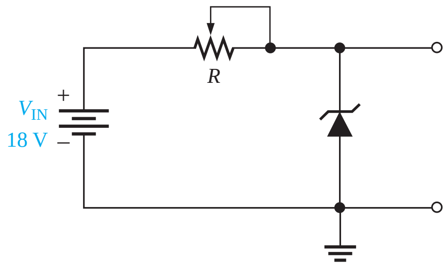
6. Determine the minimum input voltage required for regulation to be established in Figure 3–68. Assume an ideal zener diode with $I_{ZK} = 1.5$ mA and $V_Z = 14$ V.

▶ FIGURE 3–68



7. Repeat Problem 6 with $Z_Z = 20\ \Omega$ and $V_Z = 14$ V at 30 mA.

▶ FIGURE 3–69



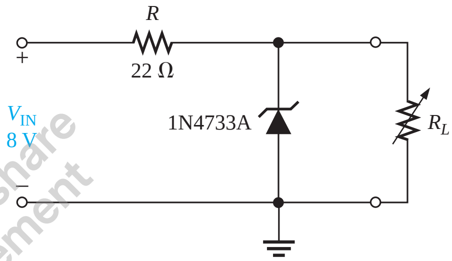
8. To what value must R be adjusted in Figure 3–69 to make $I_Z = 40$ mA? Assume $V_Z = 12$ V at 30 mA and $Z_Z = 30\ \Omega$.

9. A 20 V peak sinusoidal voltage is applied to the circuit in Figure 3–69 in place of the dc source. Draw the output waveform. Use the parameter values established in Problem 8.

10. A loaded zener regulator is shown in Figure 3–70. $V_Z = 5.1$ V at $I_Z = 49$ mA, $I_{ZK} = 1$ mA, $Z_Z = 7\ \Omega$, and $I_{ZM} = 70$ mA. Determine the minimum and maximum permissible load currents.

▶ FIGURE 3–70

Multisim file circuits are identified with a logo and are in the Problems folder on the companion website. Filenames correspond to figure numbers (e.g., F03-70).



11. Find the load regulation expressed as a percentage in Problem 10. Refer to Chapter 2, Equation 2–15.

12. Analyze the circuit in Figure 3–70 for percent line regulation using an input voltage from 6 V to 12 V with no load. Refer to Chapter 2, Equation 2–14.

13. The no-load output voltage of a certain zener regulator is 8.23 V, and the full-load output is 7.98 V. Calculate the load regulation expressed as a percentage. Refer to Chapter 2, Equation 2–15.

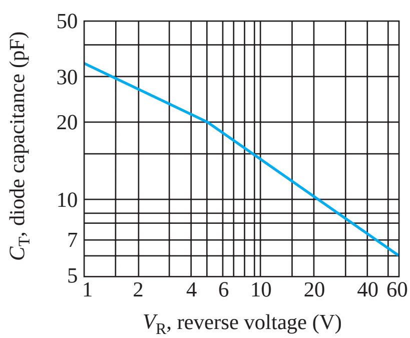
14. In a certain zener regulator, the output voltage changes 0.2 V when the input voltage goes from 5 V to 10 V. What is the input regulation expressed as a percentage? Refer to Chapter 2, Equation 2–14.

15. The output voltage of a zener regulator is 3.6 V at no load and 3.4 V at full load. Determine the load regulation expressed as a percentage. Refer to Chapter 2, Equation 2–15.

Section 3–3 The Varactor Diode

16. Figure 3–71 is a curve of reverse voltage versus capacitance for a certain varactor. Determine the change in capacitance if V_R varies from 5 V to 20 V.

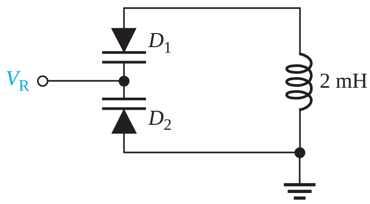
▶ FIGURE 3–71



17. Refer to Figure 3–71 and determine the approximate value of V_R that produces 25 pF.

18. What capacitance value is required for each of the varactors in Figure 3–72 to produce a resonant frequency of 1 MHz?

▶ FIGURE 3–72

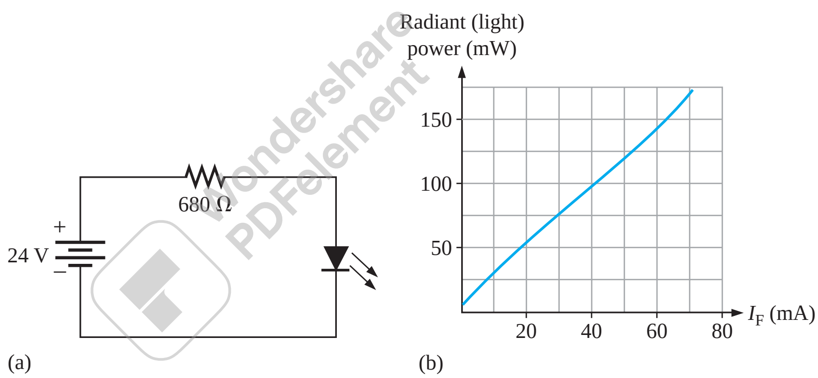


19. At what value must the voltage V_R be set in Problem 18 if the varactors have the characteristic curve in Figure 3–72?

Section 3–4 Optical Diodes

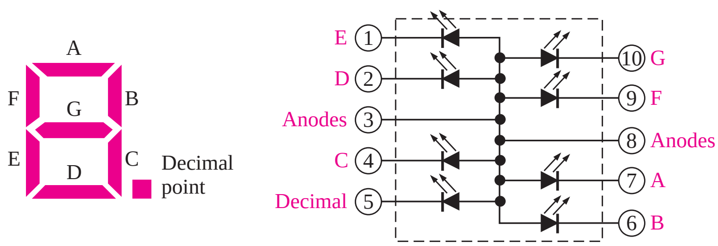
20. The LED in Figure 3–73(a) has a light-producing characteristic as shown in part (b). Neglecting the forward voltage drop of the LED, determine the amount of radiant (light) power produced in mW.

▶ FIGURE 3–73



21. Determine how to connect the seven-segment display in Figure 3–74 to display "5." The maximum continuous forward current for each LED is 30 mA and a +5 V dc source is to be used.

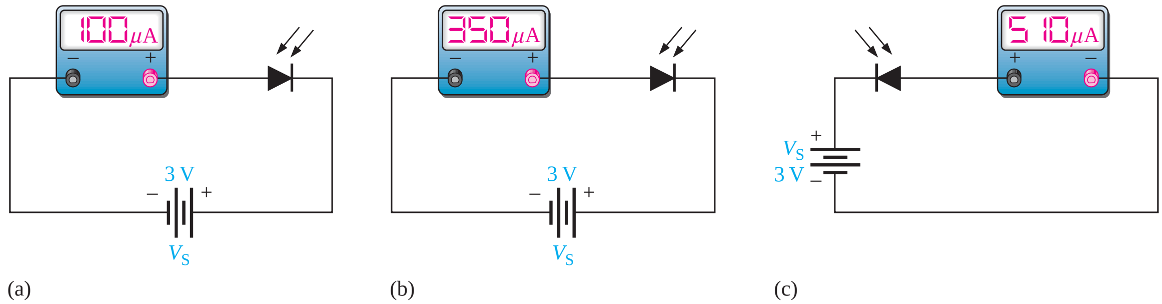
▶ FIGURE 3–74



22. Specify the number of limiting resistors and their value for a series-parallel array of 48 red LEDs using a 9 V dc source for a forward current of 20 mA.

23. Develop a yellow LED traffic-light array using a minimum number of limiting resistors that operates from a 24 V supply and consists of 100 LEDs with $I_F = 30$ mA and an equal number of LEDs in each parallel branch. Show the circuit and the resistor values.

24. For a certain photodiode at a given irradiance, the reverse resistance is 200 kΩ and the reverse voltage is 10 V. What is the current through the device?

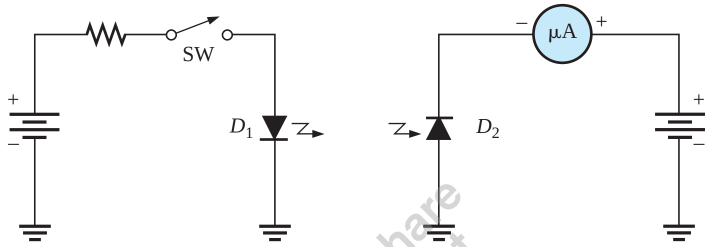


▲ FIGURE 3–75

25. What is the resistance of each photodiode in Figure 3–75?

26. When the switch in Figure 3–76 is closed, will the microammeter reading increase or decrease? Assume D_1 and D_2 are optically coupled.

▶ FIGURE 3–76



Section 3–5 Other Types of Diodes

27. The *V-I* characteristic of a certain tunnel diode shows that the current changes from 0.25 mA to 0.15 mA when the voltage changes from 125 mV to 200 mV. What is the resistance?

28. In what type of circuit are tunnel diodes commonly used?

29. What purpose do the reflective surfaces in the laser diode serve? Why is one end only partially reflective?

Section 3–6 Troubleshooting

30. For each set of measured voltages at the points (1, 2, and 3) indicated in Figure 3–77, determine if they are correct and if not, identify the most likely fault(s). State what you would do to correct the problem once it is isolated. The zener is rated at 12 V.

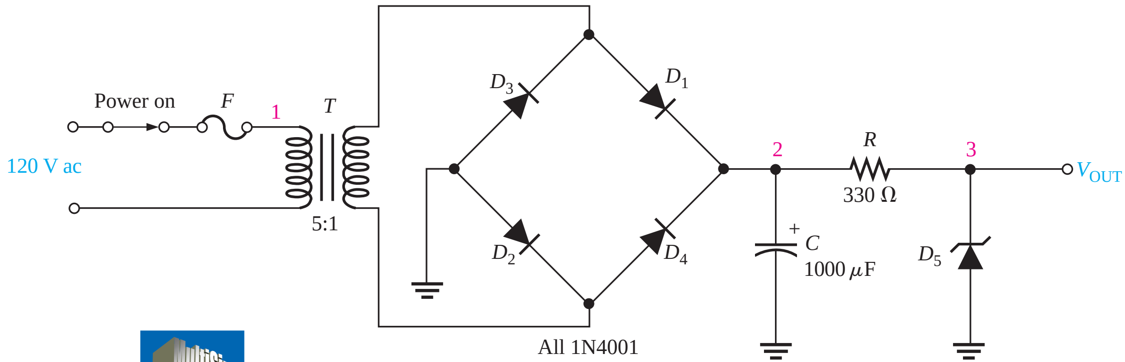
   (a) V_1 = 120 V rms, V_2 = 30 V dc, V_3 = 12 V dc

   (b) V_1 = 120 V rms, V_2 = 30 V dc, V_3 = 30 V dc

   (c) V_1 = 0 V, V_2 = 0 V, V_3 = 0 V

   (d) V_1 = 120 V rms, V_2 = 30 V peak full-wave 120 Hz, V_3 = 12 V, 120 Hz pulsating voltage

   (e) V_1 = 120 V rms, V_2 = 9 V, V_3 = 0 V



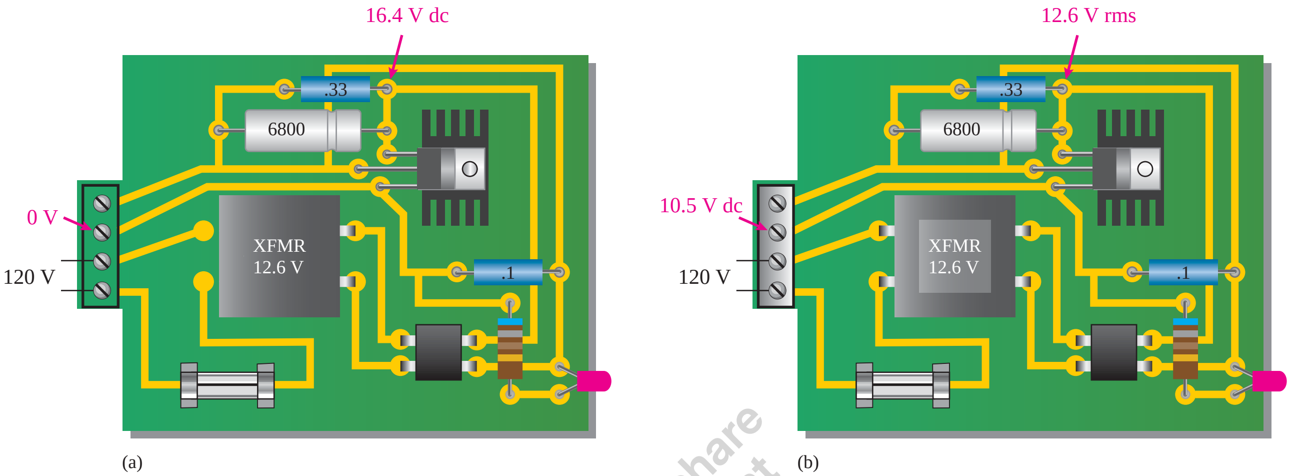
▲ FIGURE 3–77

31. What is the output voltage in Figure 3–77 for each of the following faults?

(a) D_5 open **(b)** R open **(c)** C leaky **(d)** C open
(e) D_3 open **(f)** D_2 open **(g)** T open **(h)** F open

APPLICATION ACTIVITY PROBLEMS

32. Based on the indicated voltage measurements with respect to ground in Figure 3–78(a), determine the probable fault(s).



▲ **FIGURE 3–78**

33. Determine the probable fault(s) indicated by the voltage measurements in Figure 3–78(b).

34. List the possible reasons for the LED in Figure 3–78 not emitting light when the power supply is plugged in.

35. If a 1 kΩ load resistor is connected from the output pin to ground on a properly operating power supply circuit like shown in Figure 3–78, how much power will the 7812 regulator dissipate?

DATASHEET PROBLEMS

36. Refer to the zener diode datasheet in Figure 3–7.

(a) What is the maximum dc power dissipation at 25°C for a 1N4738A?

(b) Determine the maximum power dissipation at 70°C and at 100°C for a 1N4751A.

(c) What is the minimum current required by the 1N4738A for regulation?

(d) What is the maximum current for the 1N4750A at 25°C?

(e) The current through a 1N4740A changes from 25 mA to 0.25 mA. How much does the zener impedance change?

37. Refer to the varactor diode datasheet in Figure 3–24.

(a) What is the maximum forward current for the 832A?

(b) What is the maximum capacitance of an 830A at a reverse voltage of 2 V?

(c) What is the maximum capacitance range of an 836A?

38. Refer to the LED datasheet in Figure 3–34.

(a) Can 9 V be applied in reverse across an TSMF1000 LED?

(b) Determine the typical value of series resistor for the TSMF1000 when a voltage of 5.1 V is used to forward-bias the diode with $I_F = 20$ mA.

(c) Assume the forward current is 50 mA and the forward voltage drop is 1.5 V at an ambient temperature of 15°C. Is the maximum power rating exceeded?

(d) Determine the radiant intensity for a forward current of 40 mA.

(e) What is the radiant intensity at an angle of 20° from the axis if the forward current is 100 mA?

39. Refer to the photodiode datasheet in Figure 3–47.

(a) An TEMD1000 is connected in series with a 1 kΩ resistor and a reverse-bias voltage source. There is no incident light on the diode. What is the maximum voltage drop across the resistor?

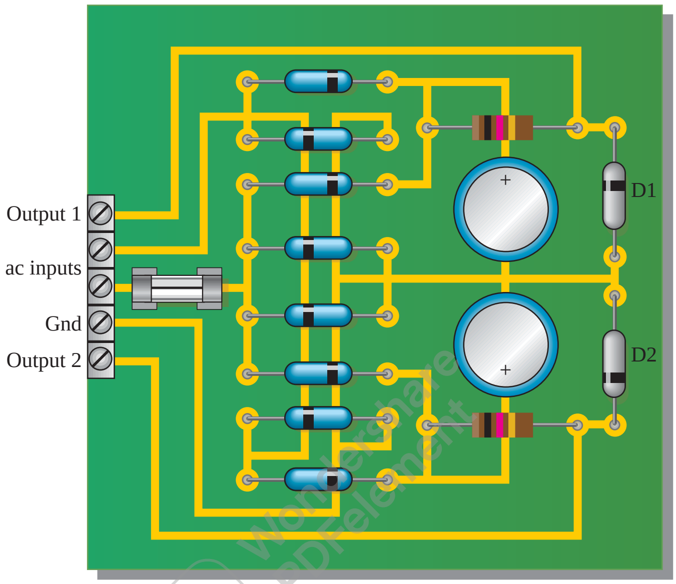
(b) At what wavelength will the reverse current be the greatest for a given irradiance?

(c) At what wavelength is relative spectral sensitivity of the TEMD1000 equal to 0.4?

ADVANCED PROBLEMS

40. Develop the schematic for the circuit board in Figure 3–79 and determine what type of circuit it is.

▶ FIGURE 3–79



Rectifier diodes: 1N4001A
Zener diodes: D1-1N4736A, D2-1N4749A
Filter capacitors: 100 μF

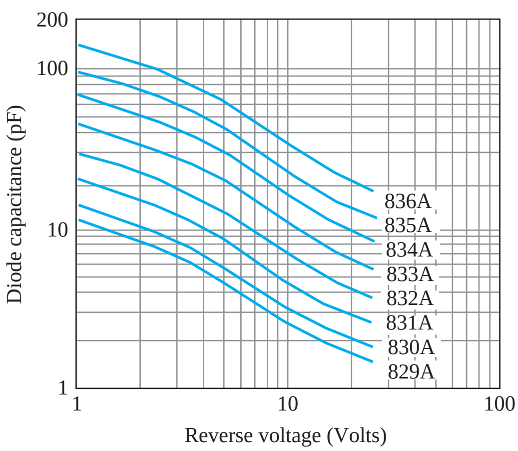
41. If a 30 V rms, 60 Hz input voltage is connected to the ac inputs, determine the output voltages on the circuit board in Figure 3–79.

42. If each output of the board in Figure 3–79 is loaded with 10 kΩ, what fuse rating should be used?

43. Design a zener voltage regulator to meet the following specifications: The input voltage is 24 V dc, the load current is 35 mA, and the load voltage is 8.2 V.

44. The varactor-tuned band-pass filter in Figure 3–27 is to be redesigned to produce a bandwidth of from 350 kHz to 850 kHz within a 10% tolerance. Specify what change you would have to make using the graph in Figure 3–80.

▶ FIGURE 3–80



SECTION 4–1 CHECKUP
Answers can be found at www.pearsonhighered.com/floyd.

1. Name the two types of BJTs according to their structure.
2. The BJT is a three-terminal device. Name the three terminals.
3. What separates the three regions in a BJT?

4–2 Basic BJT Operation

In order for a BJT to operate properly as an amplifier, the two *pn* junctions must be correctly biased with external dc voltages. In this section, we mainly use the *npn* transistor for illustration. The operation of the *pnp* is the same as for the *npn* except that the roles of the electrons and holes, the bias voltage polarities, and the current directions are all reversed.

After completing this section, you should be able to

- **Discuss basic BJT operation**
- Describe forward-reverse bias
  - Show how to bias *pnp* and *npn* BJTs with dc sources
- Explain the internal operation of a BJT
  - Discuss the hole and electron movement
- Discuss transistor currents
  - Calculate any of the transistor currents if the other two are known

Biasing

Figure 4–3 shows a bias arrangement for both *npn* and *pnp* BJTs for operation as an **amplifier.** Notice that in both cases the base-emitter (BE) junction is forward-biased and the base-collector (BC) junction is reverse-biased. This condition is called *forward-reverse bias.*

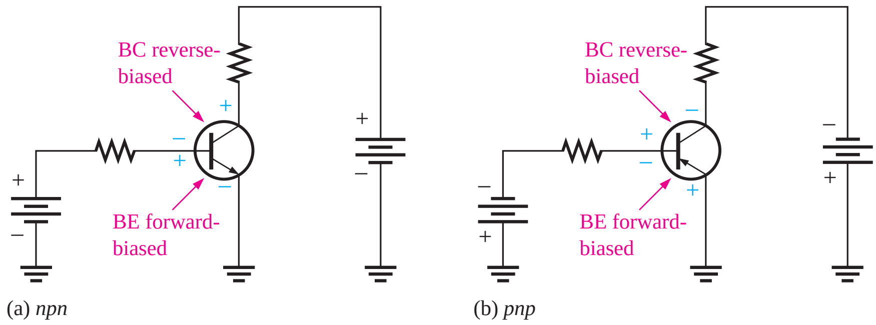
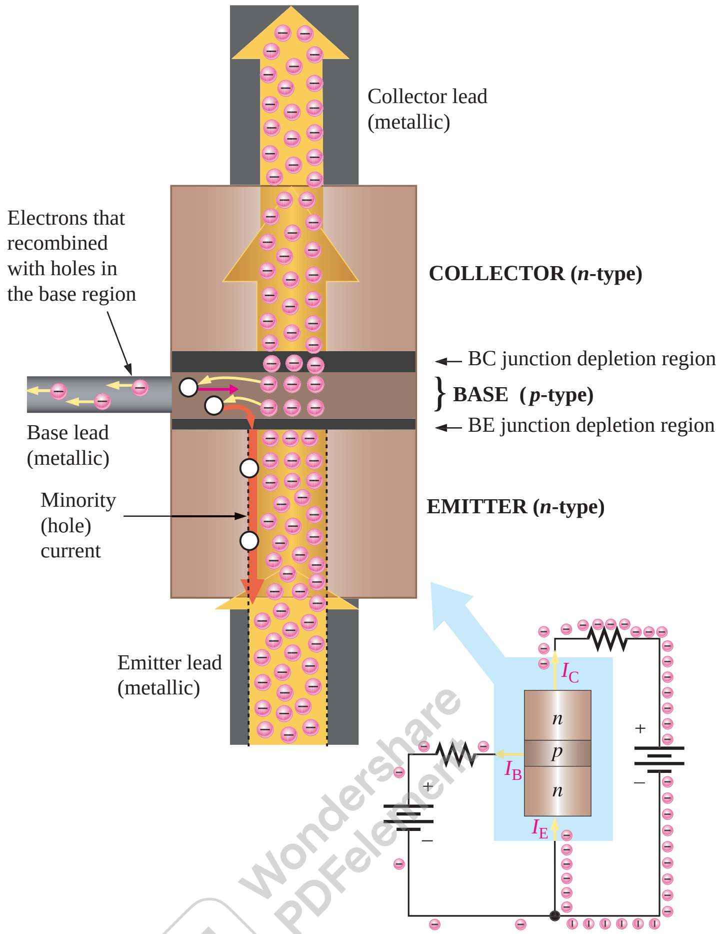


FIGURE 4–3
Forward-reverse bias of a BJT.

Operation

To understand how a transistor operates, let's examine what happens inside the *npn* structure. The heavily doped *n*-type emitter region has a very high density of conduction-band (free) electrons, as indicated in Figure 4–4. These free electrons easily diffuse through the forward-based BE junction into the lightly doped and very thin *p*-type base region, as indicated by the wide arrow. The base has a low density of holes, which are the majority carriers, as represented by the white circles. A small percentage of the total number of free electrons injected into the base region recombine with holes and move as valence electrons through the base region and into the emitter region as hole current, indicated by the red arrows.



▲ **FIGURE 4–4**

BJT operation showing electron flow.

When the electrons that have recombined with holes as valence electrons leave the crystalline structure of the base, they become free electrons in the metallic base lead and produce the external base current. Most of the free electrons that have entered the base do not recombine with holes because the base is very thin. As the free electrons move toward the reverse-biased BC junction, they are swept across into the collector region by the attraction of the positive collector supply voltage. The free electrons move through the collector region, into the external circuit, and then return into the emitter region along with the base current, as indicated. The emitter current is slightly greater than the collector current because of the small base current that splits off from the total current injected into the base region from the emitter.

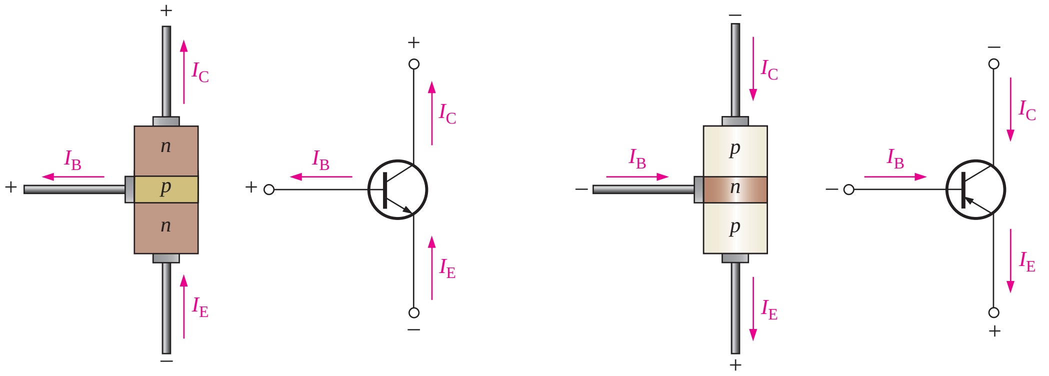
Transistor Currents

The directions of the currents in an *npn* transistor and its schematic symbol are as shown in Figure 4–5(a); those for a *pnp* transistor are shown in Figure 4–5(b). Notice that the arrow on the emitter inside the transistor symbols points in the direction of conventional current. These diagrams show that the emitter current (I_E) is the sum of the collector current (I_C) and the base current (I_B), expressed as follows:

Equation 4–1

$$I_E = I_C + I_B$$

As mentioned before, I_B is very small compared to I_E or I_C. The capital-letter subscripts indicate dc values.



(a) *npn* (b) *pnp*

▲ **FIGURE 4–5**

Transistor currents.

SECTION 4–2 CHECKUP

1. What are the bias conditions of the base-emitter and base-collector junctions for a transistor to operate as an amplifier?
2. Which is the largest of the three transistor currents?
3. Is the base current smaller or larger than the emitter current?
4. Is the base region much thinner or much wider than the collector and emitter regions?
5. If the collector current is 1 mA and the base current is 10 μA, what is the emitter current?

4–3 BJT Characteristics and Parameters

Two important parameters, β_{DC} (dc current gain) and α_{DC} are introduced and used to analyze a BJT circuit. Also, transistor characteristic curves are covered, and you will learn how a BJT's operation can be determined from these curves. Finally, maximum ratings of a BJT are discussed.

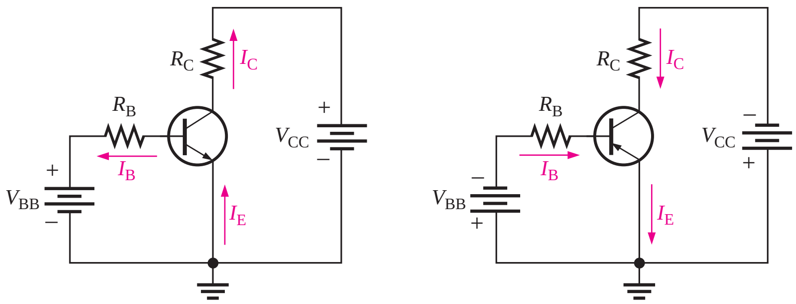
After completing this section, you should be able to

- **Discuss basic BJT parameters and characteristics and analyze transistor circuits**
- Define *dc beta* (β_{DC}) and *dc alpha* (α_{DC})
  - Calculate (β_{DC}) and (α_{DC}) based on transistor current
- Describe a basic dc model of a BJT
- Analyze BJT circuits
  - Identify transistor currents and voltages ◆ Calculate each transistor current
  - Calculate each transistor voltage
- Interpret collector characteristic curves
  - Discuss the linear region ◆ Explain saturation and cutoff in relation to the curves
- Describe the cutoff condition in a BJT circuit
- Describe the saturation condition in a BJT circuit
- Discuss the dc load line and apply it to circuit analysis
- Discuss how β_{DC} changes with temperature
- Explain and apply maximum transistor ratings
- Derate a transistor for power dissipation
- Interpret a BJT datasheet

When a transistor is connected to dc bias voltages, as shown in Figure 4–6 for both *npn* and *pnp* types, V_{BB} forward-biases the base-emitter junction, and V_{CC} reverse-biases the base-collector junction. Although in this chapter we are using separate battery symbols to represent the bias voltages, in practice the voltages are often derived from a single dc power supply. For example, V_{CC} is normally taken directly from the power supply output and V_{BB} (which is smaller) can be produced with a voltage divider. Bias circuits are examined thoroughly in Chapter 5.

FIGURE 4–6

Transistor dc bias circuits.



DC Beta (β_{DC}) and DC Alpha (α_{DC})

The dc current **gain** of a transistor is the ratio of the dc collector current (I_C) to the dc base current (I_B) and is designated dc **beta** (β_{DC}).

Equation 4–2

$$\boldsymbol{\beta_{DC} = \frac{I_C}{I_B}}$$

Typical values of β_{DC} range from less than 20 to 200 or higher. β_{DC} is usually designated as an equivalent hybrid (*h*) parameter, h_{FE}, on transistor datasheets. *h*-parameters are covered in Chapter 6. All you need to know now is that

$$h_{FE} = \beta_{DC}$$

The ratio of the dc collector current (I_C) to the dc emitter current (I_E) is the dc **alpha** (α_{DC}). The alpha is a less-used parameter than beta in transistor circuits.

$$\alpha_{DC} = \frac{I_C}{I_E}$$

Typically, values of α_{DC} range from 0.95 to 0.99 or greater, but α_{DC} is always less than 1. The reason is that I_C is always slightly less than I_E by the amount of I_B. For example, if $I_E = 100$ mA and $I_B = 1$ mA, then $I_C = 99$ mA and $\alpha_{DC} = 0.99$.

EXAMPLE 4–1

Determine the dc current gain β_{DC} and the emitter current I_E for a transistor where $I_B = 50\ \mu A$ and $I_C = 3.65$ mA.

Solution

$$\beta_{DC} = \frac{I_C}{I_B} = \frac{3.65\text{ mA}}{50\ \mu\text{A}} = \mathbf{73}$$

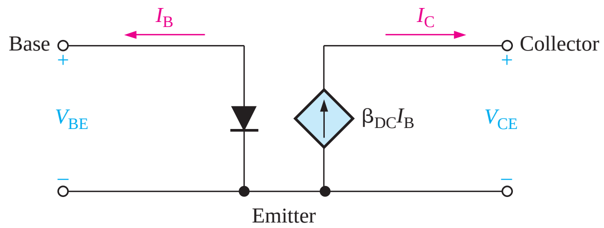
$$I_E = I_C + I_B = 3.65\text{ mA} + 50\ \mu\text{A} = \mathbf{3.70\ mA}$$

*Related Problem** A certain transistor has a β_{DC} of 200. When the base current is 50 μA, determine the collector current.

***Answers can be found at www.pearsonhighered.com/floyd**

Transistor DC Model

You can view the unsaturated BJT as a device with a current input and a dependent current source in the output circuit, as shown in Figure 4–7 for an *npn*.The input circuit is a forward-biased diode through which there is base current. The output circuit is a dependent current source (diamond-shaped element) with a value that is dependent on the base current, I_B, and equal to $\beta_{DC}I_B$. Recall that independent current source symbols have a circular shape.



◀ **FIGURE 4–7**

Ideal dc model of an *npn* transistor.

BJT Circuit Analysis

Consider the basic transistor bias circuit configuration in Figure 4–8. Three transistor dc currents and three dc voltages can be identified.

I_B: dc base current

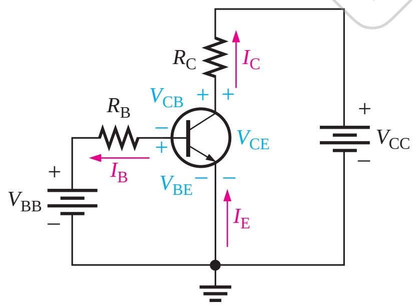
I_E: dc emitter current

I_C: dc collector current

V_{BE}: dc voltage at base with respect to emitter

V_{CB}: dc voltage at collector with respect to base

V_{CE}: dc voltage at collector with respect to emitter



◀ **FIGURE 4–8**

Transistor currents and voltages.

The base-bias voltage source, V_{BB}, forward-biases the base-emitter junction, and the collector-bias voltage source, V_{CC}, reverse-biases the base-collector junction. When the base-emitter junction is forward-biased, it is like a forward-biased diode and has a nominal forward voltage drop of

$$\mathbf{V_{BE} \cong 0.7\ V} \qquad \textbf{Equation 4–3}$$

Although in an actual transistor V_{BE} can be as high as 0.9 V and is dependent on current, we will use 0.7 V throughout this text in order to simplify the analysis of the basic concepts. Keep in mind that the characteristic of the base-emitter junction is the same as a normal diode curve like the one in Figure 2-12.

Since the emitter is at ground (0 V), by Kirchhoff's voltage law, the voltage across R_B is

$$V_{R_B} = V_{BB} - V_{BE}$$

Also, by Ohm's law,

$$V_{R_B} = I_B R_B$$

Substituting for V_{R_B} yields

$$I_B R_B = V_{BB} - V_{BE}$$

Solving for I_B,

Equation 4–4

$$\mathbf{I_B = \frac{V_{BB} - V_{BE}}{R_B}}$$

The voltage at the collector with respect to the grounded emitter is

$$V_{CE} = V_{CC} - V_{R_C}$$

Since the drop across R_C is

$$V_{R_C} = I_C R_C$$

the voltage at the collector with respect to the emitter can be written as

Equation 4–5

$$\mathbf{V_{CE} = V_{CC} - I_C R_C}$$

where $I_C = \beta_{DC} I_B$.

The voltage across the reverse-biased collector-base junction is

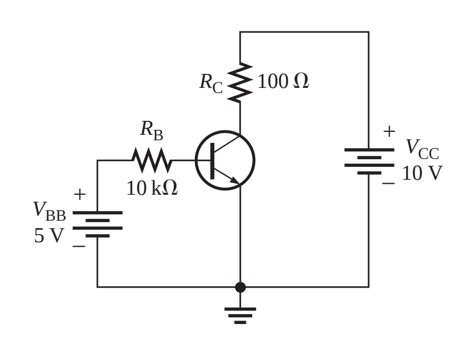
Equation 4–6

$$\mathbf{V_{CB} = V_{CE} - V_{BE}}$$

EXAMPLE 4–2

Determine I_B, I_C, I_E, V_{BE}, V_{CE}, and V_{CB} in the circuit of Figure 4–9. The transistor has a $\beta_{DC} = 150$.

▶ **FIGURE 4–9**



Solution From Equation 4–3, $V_{BE} \cong$ **0.7 V.** Calculate the base, collector, and emitter currents as follows:

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5\text{ V} - 0.7\text{ V}}{10\text{ k}\Omega} = \mathbf{430\ \mu A}$$

$$I_C = \beta_{DC} I_B = (150)(430\ \mu\text{A}) = \mathbf{64.5\ mA}$$

$$I_E = I_C + I_B = 64.5\text{ mA} + 430\ \mu\text{A} = \mathbf{64.9\ mA}$$

Solve for V_{CE} and V_{CB}.

$$V_{CE} = V_{CC} - I_C R_C = 10\text{ V} - (64.5\text{ mA})(100\ \Omega) = 10\text{ V} - 6.45\text{ V} = \mathbf{3.55\ V}$$

$$V_{CB} = V_{CE} - V_{BE} = 3.55\text{ V} - 0.7\text{ V} = \mathbf{2.85\ V}$$

Since the collector is at a higher voltage than the base, the collector-base junction is reverse-biased.

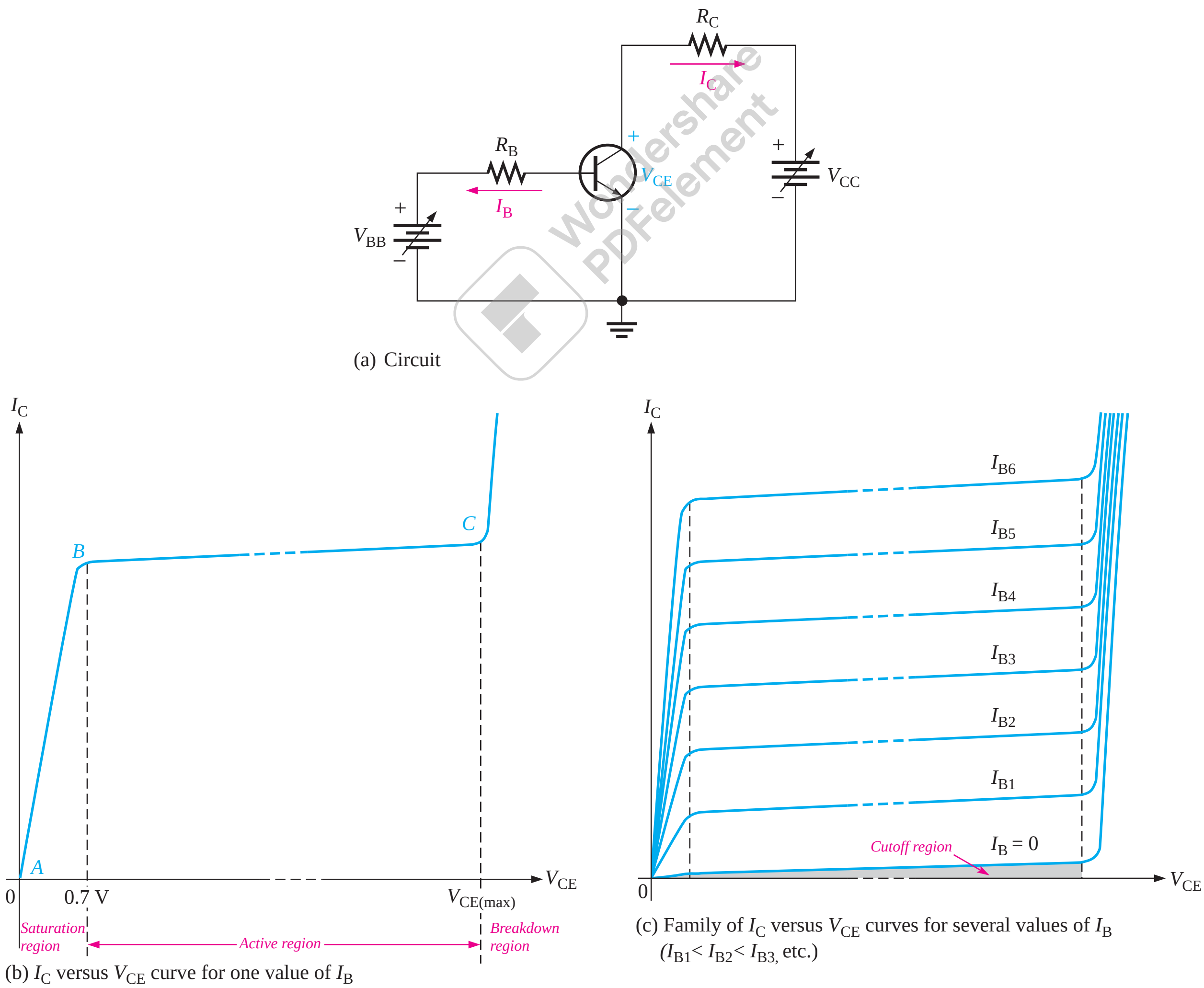
Related Problem Determine I_B, I_C, I_E, V_{CE}, and V_{CB} in Figure 4–9 for the following values: $R_B = 22\ \text{k}\Omega$, $R_C = 220\ \Omega$, $V_{BB} = 6$ V, $V_{CC} = 9$ V, and $\beta_{DC} = 90$.

Open the Multisim file E04-02 in the Examples folder on the companion website. Measure each current and voltage and compare with the calculated values.

Collector Characteristic Curves

Using a circuit like that shown in Figure 4–10(a), a set of *collector characteristic curves* can be generated that show how the collector current, I_C, varies with the collector-to-emitter voltage, V_{CE}, for specified values of base current, I_B. Notice in the circuit diagram that both V_{BB} and V_{CC} are variable sources of voltage.

Assume that V_{BB} is set to produce a certain value of I_B and V_{CC} is zero. For this condition, both the base-emitter junction and the base-collector junction are forward-biased because the base is at approximately 0.7 V while the emitter and the collector are at 0 V. The base current is through the base-emitter junction because of the low impedance path to



▲ **FIGURE 4–10**

Collector characteristic curves.

ground and, therefore, I_C is zero. When both junctions are forward-biased, the transistor is in the saturation region of its operation. **Saturation** is the state of a BJT in which the collector current has reached a maximum and is independent of the base current.

As V_{CC} is increased, V_{CE} increases as the collector current increases. This is indicated by the portion of the characteristic curve between points *A* and *B* in Figure 4–10(b). I_C increases as V_{CC} is increased because V_{CE} remains less than 0.7 V due to the forward-biased base-collector junction.

Ideally, when V_{CE} exceeds 0.7 V, the base-collector junction becomes reverse-biased and the transistor goes into the *active*, or **linear**, *region* of its operation. Once the base-collector junction is reverse-biased, I_C levels off and remains essentially constant for a given value of I_B as V_{CE} continues to increase. Actually, I_C increases very slightly as V_{CE} increases due to widening of the base-collector depletion region. This results in fewer holes for recombination in the base region which effectively causes a slight increase in β_{DC}. This is shown by the portion of the characteristic curve between points *B* and *C* in Figure 4–10(b). For this portion of the characteristic curve, the value of I_C is determined only by the relationship expressed as $I_C = \beta_{DC} I_B$.

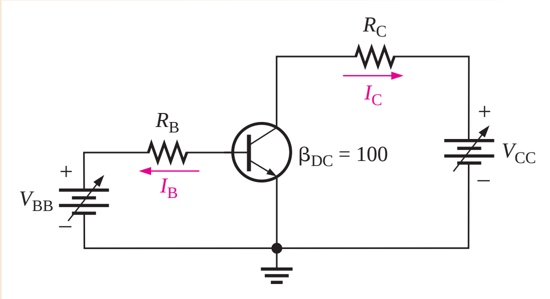
When V_{CE} reaches a sufficiently high voltage, the reverse-biased base-collector junction goes into breakdown; and the collector current increases rapidly as indicated by the part of the curve to the right of point *C* in Figure 4–10(b). A transistor should never be operated in this breakdown region.

A family of collector characteristic curves is produced when I_C versus V_{CE} is plotted for several values of I_B, as illustrated in Figure 4–10(c). When $I_B = 0$, the transistor is in the cutoff region although there is a very small collector leakage current as indicated. **Cutoff** is the nonconducting state of a transistor. The amount of collector leakage current for $I_B = 0$ is exaggerated on the graph for illustration.

EXAMPLE 4–3

Sketch an ideal family of collector curves for the circuit in Figure 4–11 for $I_B = 5\ \mu A$ to $25\ \mu A$ in $5\ \mu A$ increments. Assume $\beta_{DC} = 100$ and that V_{CE} does not exceed breakdown.

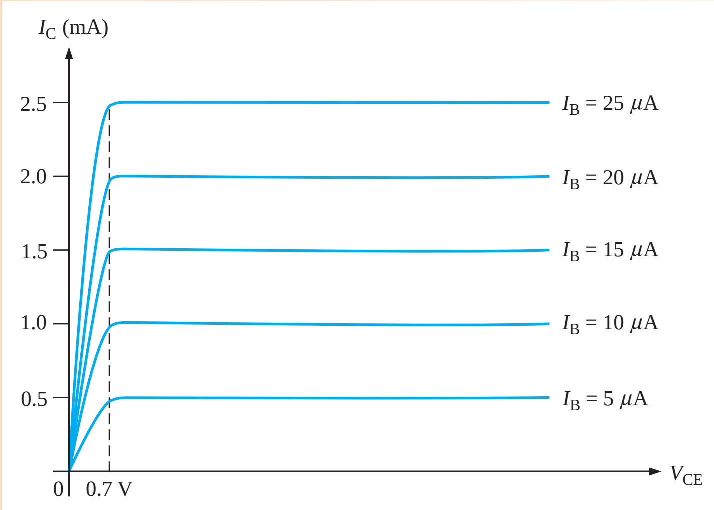
▶ FIGURE 4–11



Solution Using the relationship $I_C = \beta_{DC} I_B$, values of I_C are calculated and tabulated in Table 4–1. The resulting curves are plotted in Figure 4–12.

▶ TABLE 4–1

I_B	I_C
5 μA	0.5 mA
10 μA	1.0 mA
15 μA	1.5 mA
20 μA	2.0 mA
25 μA	2.5 mA

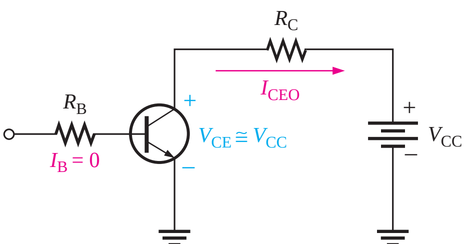


▲ **FIGURE 4–12**

Related Problem Where would the curve for $I_B = 0$ appear on the graph in Figure 4–12, neglecting collector leakage current?

Cutoff

As previously mentioned, when $I_B = 0$, the transistor is in the cutoff region of its operation. This is shown in Figure 4–13 with the base lead open, resulting in a base current of zero. Under this condition, there is a very small amount of collector leakage current, I_{CEO}, due mainly to thermally produced carriers. Because I_{CEO} is extremely small, it will usually be neglected in circuit analysis so that $V_{CE} = V_{CC}$. In cutoff, neither the base-emitter nor the base-collector junctions are forward-biased. The subscript CEO represents collector-to-emitter with the base open.



◄ **FIGURE 4–13**

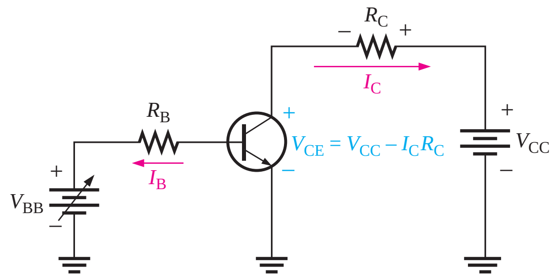
Cutoff: Collector leakage current (I_{CEO}) is extremely small and is usually neglected. Base-emitter and base-collector junctions are reverse-biased.

Saturation

When the base-emitter junction becomes forward-biased and the base current is increased, the collector current also increases ($I_C = \beta_{DC} I_B$) and V_{CE} decreases as a result of more drop across the collector resistor ($V_{CE} = V_{CC} - I_C R_C$). This is illustrated in Figure 4–14. When V_{CE} reaches its saturation value, $V_{CE(sat)}$, the base-collector junction becomes forward-biased and I_C can increase no further even with a continued increase in I_B. At the point of saturation, the relation $I_C = \beta_{DC} I_B$ is no longer valid. $V_{CE(sat)}$ for a transistor occurs somewhere below the knee of the collector curves, and it is usually only a few tenths of a volt.

▶ **FIGURE 4–14**

Saturation: As I_B increases due to increasing V_{BB}, I_C also increases and V_{CE} decreases due to the increased voltage drop across R_C. When the transistor reaches saturation, I_C can increase no further regardless of further increase in I_B. Base-emitter and base-collector junctions are forward-biased.

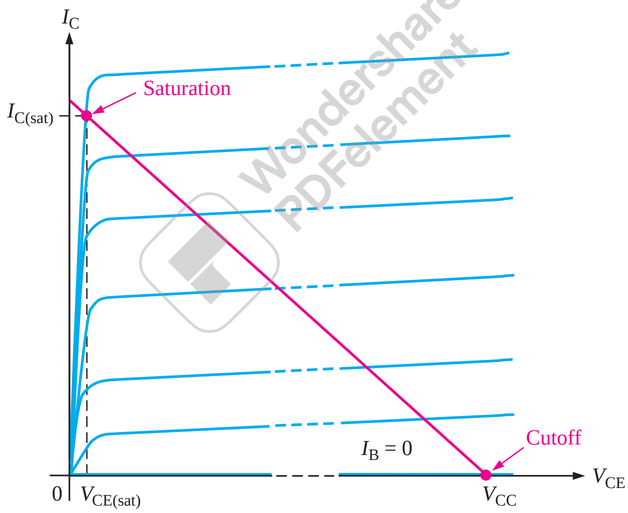


DC Load Line

Cutoff and saturation can be illustrated in relation to the collector characteristic curves by the use of a load line. Figure 4–15 shows a dc load line drawn on a family of curves connecting the cutoff point and the saturation point. The bottom of the load line is at ideal cutoff where $I_C = 0$ and $V_{CE} = V_{CC}$. The top of the load line is at saturation where $I_C = I_{C(sat)}$ and $V_{CE} = V_{CE(sat)}$. In between cutoff and saturation along the load line is the *active region* of the transistor's operation. Load line operation is discussed more in Chapter 5.

▶ **FIGURE 4–15**

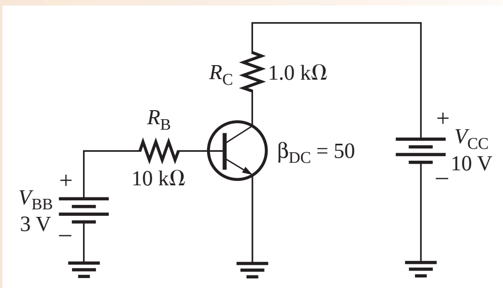
DC load line on a family of collector characteristic curves illustrating the cutoff and saturation conditions.



EXAMPLE 4–4

Determine whether or not the transistor in Figure 4–16 is in saturation. Assume $V_{CE(sat)} = 0.2$ V.

▶ **FIGURE 4–16**



Solution First, determine $I_{C(sat)}$.

$$I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C} = \frac{10\text{ V} - 0.2\text{ V}}{1.0\text{ k}\Omega} = \frac{9.8\text{ V}}{1.0\text{ k}\Omega} = 9.8\text{ mA}$$

Now, see if I_B is large enough to produce $I_{C(sat)}$.

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{3\text{ V} - 0.7\text{ V}}{10\text{ k}\Omega} = \frac{2.3\text{ V}}{10\text{ k}\Omega} = 0.23\text{ mA}$$

$$I_C = \beta_{DC} I_B = (50)(0.23\text{ mA}) = 11.5\text{ mA}$$

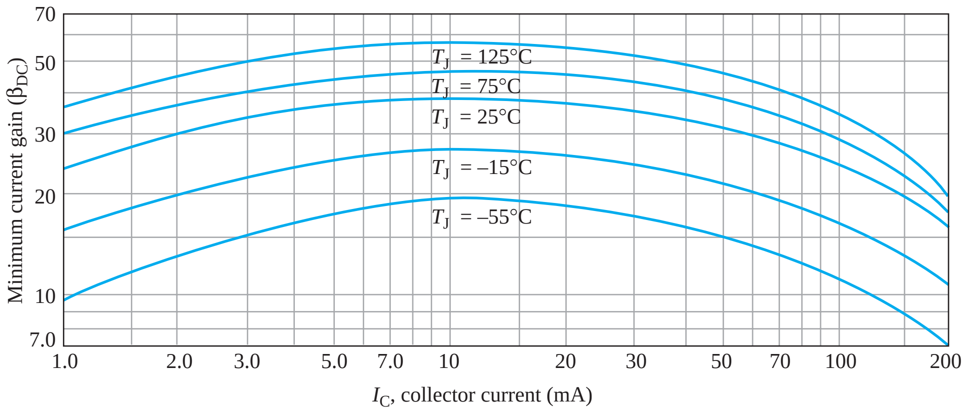
This shows that with the specified β_{DC}, this base current is capable of producing an I_C greater than $I_{C(sat)}$. Therefore, the **transistor is saturated,** and the collector current value of 11.5 mA is never reached. If you further increase I_B, the collector current remains at its saturation value of 9.8 mA.

Related Problem Determine whether or not the transistor in Figure 4–16 is saturated for the following values: $\beta_{DC} = 125$, $V_{BB} = 1.5$ V, $R_B = 6.8$ kΩ, $R_C = 180\ \Omega$, and $V_{CC} = 12$ V.

Open the Multisim file E04-04 in the Examples folder on the companion website. Determine if the transistor is in saturation and explain how you did this.

More About β_{DC}

The β_{DC} or h_{FE} is an important BJT parameter that we need to examine further. β_{DC} is not truly constant but varies with both collector current and with temperature. Keeping the junction temperature constant and increasing I_C causes β_{DC} to increase to a maximum. A further increase in I_C beyond this maximum point causes β_{DC} to decrease. If I_C is held constant and the temperature is varied, β_{DC} changes directly with the temperature. If the temperature goes up, β_{DC} goes up and vice versa. Figure 4–17 shows the variation of β_{DC} with I_C and junction temperature (T_J) for a typical BJT.



▲ **FIGURE 4–17**

Variation of β_{DC} with I_C for several temperatures.

A transistor datasheet usually specifies β_{DC} (h_{FE}) at specific I_C values. Even at fixed values of I_C and temperature, β_{DC} varies from one device to another for a given type of transistor due to inconsistencies in the manufacturing process that are unavoidable. The β_{DC} specified at a certain value of I_C is usually the minimum value, $\beta_{DC(min)}$, although the maximum and typical values are also sometimes specified.

Maximum Transistor Ratings

A BJT, like any other electronic device, has limitations on its operation. These limitations are stated in the form of maximum ratings and are normally specified on the manufacturer's datasheet. Typically, maximum ratings are given for collector-to-base voltage, collector-to-emitter voltage, emitter-to-base voltage, collector current, and power dissipation.

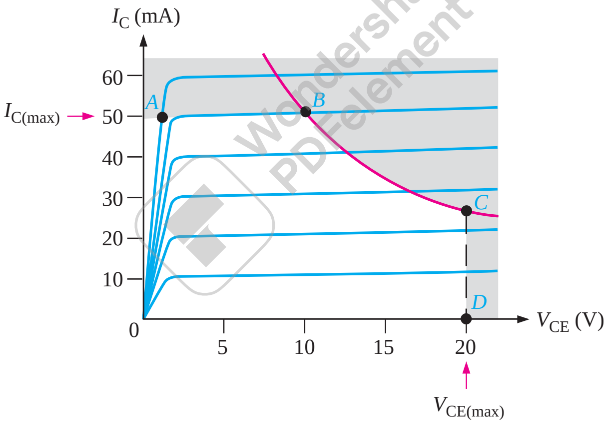
The product of V_{CE} and I_C must not exceed the maximum power dissipation. Both V_{CE} and I_C cannot be maximum at the same time. If V_{CE} is maximum, I_C can be calculated as

$$I_C = \frac{P_{D(max)}}{V_{CE}}$$

If I_C is maximum, V_{CE} can be calculated by rearranging the previous equation as follows:

$$V_{CE} = \frac{P_{D(max)}}{I_C}$$

For any given transistor, a maximum power dissipation curve can be plotted on the collector characteristic curves, as shown in Figure 4–18(a). These values are tabulated in Figure 4–18(b). Assume $P_{D(max)}$ is 500 mW, $V_{CE(max)}$ is 20 V, and $I_{C(max)}$ is 50 mA. The curve shows that this particular transistor cannot be operated in the shaded portion of the graph. $I_{C(max)}$ is the limiting rating between points *A* and *B*, $P_{D(max)}$ is the limiting rating between points *B* and *C*, and $V_{CE(max)}$ is the limiting rating between points *C* and *D*.



(a)

$P_{D(max)}$	V_{CE}	I_C
500 mW	5 V	100 mA
500 mW	10 V	50 mA
500 mW	15 V	33 mA
500 mW	20 V	25 mA

(b)

▲ **FIGURE 4–18**

Maximum power dissipation curve and tabulated values.

EXAMPLE 4–5

A certain transistor is to be operated with $V_{CE} = 6$ V. If its maximum power rating is 250 mW, what is the most collector current that it can handle?

Solution

$$I_C = \frac{P_{D(max)}}{V_{CE}} = \frac{250 \text{ mW}}{6 \text{ V}} = \mathbf{41.7\ mA}$$

This is the maximum current for this particular value of V_{CE}. The transistor can handle more collector current if V_{CE} is reduced, as long as $P_{D(max)}$ and $I_{C(max)}$ are not exceeded.

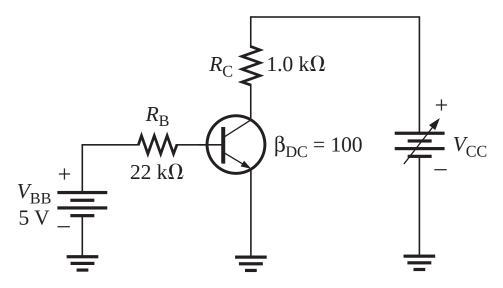
Related Problem

If $P_{D(max)} = 1$ W, how much voltage is allowed from collector to emitter if the transistor is operating with $I_C = 100$ mA?

EXAMPLE 4–6

The transistor in Figure 4–19 has the following maximum ratings: $P_{D(max)} = 800$ mW, $V_{CE(max)} = 15$ V, and $I_{C(max)} = 100$ mA. Determine the maximum value to which V_{CC} can be adjusted without exceeding a rating. Which rating would be exceeded first?

▶ FIGURE 4–19



Solution First, find I_B so that you can determine I_C.

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5\text{ V} - 0.7\text{ V}}{22\text{ k}\Omega} = 195\ \mu\text{A}$$

$$I_C = \beta_{DC}I_B = (100)(195\ \mu\text{A}) = 19.5\text{ mA}$$

I_C is much less than $I_{C(max)}$ and ideally will not change with V_{CC}. It is determined only by I_B and β_{DC}.

The voltage drop across R_C is

$$V_{R_C} = I_CR_C = (19.5\text{ mA})(1.0\text{ k}\Omega) = 19.5\text{ V}$$

Now you can determine the value of V_{CC} when $V_{CE} = V_{CE(max)} = 15$ V.

$$V_{R_C} = V_{CC} - V_{CE}$$

So,

$$V_{CC(max)} = V_{CE(max)} + (V_{R_C} = 15\text{ V} + 19.5\text{ V} = \mathbf{34.5\text{ V}}$$

V_{CC} can be increased to 34.5 V, under the existing conditions, before $V_{CE(max)}$ is exceeded. However, at this point it is not known whether or not $P_{D(max)}$ has been exceeded.

$$P_D = V_{CE(max)}I_C = (15\text{ V})(19.5\text{ mA}) = 293\text{ mW}$$

Since $P_{D(max)}$ is 800 mW, it is *not* exceeded when $V_{CC} = 34.5$ V. So, $V_{CE(max)} = 15$ V is the limiting rating in this case. If the base current is removed causing the transistor to turn off, $\mathbf{V_{CE(max)}}$ **will be exceeded first** because the entire supply voltage, V_{CC}, will be dropped across the transistor.

Related Problem The transistor in Figure 4–19 has the following maximum ratings: $P_{D(max)} = 500$ mW, $V_{CE(max)} = 25$ V, and $I_{C(max)} = 200$ mA. Determine the maximum value to which V_{CC} can be adjusted without exceeding a rating. Which rating would be exceeded first?

Derating $P_{D(max)}$

$P_{D(max)}$ is usually specified at 25°C. For higher temperatures, $P_{D(max)}$ is less. Datasheets often give derating factors for determining $P_{D(max)}$ at any temperature above 25°C. For example, a derating factor of 2 mW/°C indicates that the maximum power dissipation is reduced 2 mW for each degree Celsius increase in temperature.

EXAMPLE 4–7 A certain transistor has a $P_{D(max)}$ of 1 W at 25°C. The derating factor is 5 mW/°C. What is the $P_{D(max)}$ at a temperature of 70°C?

Solution The change (reduction) in $P_{D(max)}$ is

$$\Delta P_{D(max)} = (5\text{ mW/°C})(70°\text{C} - 25°\text{C}) = (5\text{ mW/°C})(45°\text{C}) = 225\text{ mW}$$

Therefore, the $P_{D(max)}$ at 70°C is

$$1\text{ W} - 225\text{ mW} = \mathbf{775\text{ mW}}$$

Related Problem A transistor has a $P_{D(max)} = 5$ W at 25°C. The derating factor is 10 mW/°C. What is the $P_{D(max)}$ at 70°C?

BJT Datasheet

A partial datasheet for the 2N3904 *npn* transistor is shown in Figure 4–20. Notice that the maximum collector-emitter voltage (V_{CEO}) is 40 V. The CEO subscript indicates that the voltage is measured from collector (C) to emitter (E) with the base open (O). In the text, we use $V_{CE(max)}$ for this parameter. Also notice that the maximum collector current is 200 mA.

The β_{DC} (h_{FE}) is specified for several values of I_C. As you can see, h_{FE} varies with I_C as we previously discussed.

The collector-emitter saturation voltage, $V_{CE(sat)}$ is 0.2 V maximum for $I_{C(sat)} = 10$ mA and increases with the current.

EXAMPLE 4–8 A 2N3904 transistor is used in the circuit of Figure 4–19 (Example 4–6). Determine the maximum value to which V_{CC} can be adjusted without exceeding a rating. Which rating would be exceeded first? Refer to the datasheet in Figure 4–20.

Solution From the datasheet,

$$P_{D(max)} = P_D = 625\text{ mW}$$
$$V_{CE(max)} = V_{CEO} = 40\text{ V}$$
$$I_{C(max)} = I_C = 200\text{ mA}$$

Assume $\beta_{DC} = 100$. This is a reasonably valid assumption based on the datasheet $h_{FE} = 100$ minimum for specified conditions (β_{DC} and h_{FE} are the same parameter). As you have learned, the β_{DC} has considerable variations for a given transistor, depending on circuit conditions. Under this assumption, $I_C = 19.5$ mA and $V_{R_C} = 19.5$ V from Example 4–6.

Since I_C is much less than $I_{C(max)}$ and, ideally, will not change with V_{CC}, the maximum value to which V_{CC} can be increased before $V_{CE(max)}$ is exceeded is

$$V_{CC(max)} = V_{CE(max)} + V_{R_C} = 40\text{ V} + 19.5\text{ V} = 59.5\text{ V}$$

However, at the maximum value of V_{CE}, the power dissipation is

$$P_D = V_{CE(max)}I_C = (40\text{ V})(19.5\text{ mA}) = 780\text{ mW}$$

Power dissipation exceeds the maximum of 625 mW specified on the datasheet.

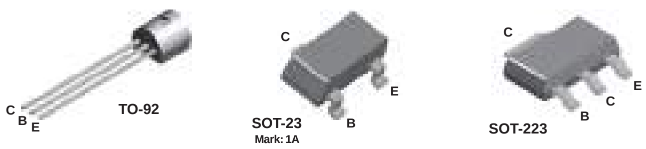
Related Problem Use the datasheet in Figure 4–20 to find the maximum P_D at 50°C.

FIGURE 4–20

Partial datasheet. For a complete 2N3904 datasheet, go to *http://www.fairchildsemi.com/ds/2N%2F2N3904.pdf*. Copyright Fairchild Semiconductor Corporation. Used by permission.

FAIRCHILD SEMICONDUCTOR™

2N3904 MMBT3904 PZT3904



NPN General Purpose Amplifier

This device is designed as a general purpose amplifier and switch. The useful dynamic range extends to 100 mA as a switch and to 100 MHz as an amplifier.

Absolute Maximum Ratings* $T_A = 25°C$ unless otherwise noted

Symbol	Parameter	Value	Units
V_{CEO}	Collector-Emitter Voltage	40	V
V_{CBO}	Collector-Base Voltage	60	V
V_{EBO}	Emitter-Base Voltage	6.0	V
I_C	Collector Current - Continuous	200	mA
T_J, T_{stg}	Operating and Storage Junction Temperature Range	-55 to +150	°C

*These ratings are limiting values above which the serviceability of any semiconductor device may be impaired.

NOTES:
1) These ratings are based on a maximum junction temperature of 150 degrees C.
2) These are steady state limits. The factory should be consulted on applications involving pulsed or low duty cycle operations.

Thermal Characteristics $T_A = 25°C$ unless otherwise noted

Symbol	Characteristic	Max			Units
		2N3904	*MMBT3904	**PZT3904	
P_D	Total Device Dissipation Derate above 25°C	625 5.0	350 2.8	1,000 8.0	mW mW/°C
$R_{\theta JC}$	Thermal Resistance, Junction to Case	83.3			°C/W
$R_{\theta JA}$	Thermal Resistance, Junction to Ambient	200	357	125	°C/W

*Device mounted on FR-4 PCB 1.6" X 1.6" X 0.06."
**Device mounted on FR-4 PCB 36 mm X 18 mm X 1.5 mm; mounting pad for the collector lead min. 6 cm².

Electrical Characteristics $T_A = 25°C$ unless otherwise noted

Symbol	Parameter	Test Conditions	Min	Max	Units
OFF CHARACTERISTICS					
$V_{(BR)CEO}$	Collector-Emitter Breakdown Voltage	$I_C = 1.0$ mA, $I_B = 0$	40		V
$V_{(BR)CBO}$	Collector-Base Breakdown Voltage	$I_C = 10\ \mu A$, $I_E = 0$	60		V
$V_{(BR)EBO}$	Emitter-Base Breakdown Voltage	$I_E = 10\ \mu A$, $I_C = 0$	6.0		V
I_{BL}	Base Cutoff Current	$V_{CE} = 30$ V, $V_{EB} = 3$V		50	nA
I_{CEX}	Collector Cutoff Current	$V_{CE} = 30$ V, $V_{EB} = 3$V		50	nA
ON CHARACTERISTICS*					
h_{FE}	DC Current Gain	$I_C = 0.1$ mA, $V_{CE} = 1.0$ V $I_C = 1.0$ mA, $V_{CE} = 1.0$ V $I_C = 10$ mA, $V_{CE} = 1.0$ V $I_C = 50$ mA, $V_{CE} = 1.0$ V $I_C = 100$ mA, $V_{CE} = 1.0$ V	40 70 100 60 30	 300 	
$V_{CE(sat)}$	Collector-Emitter Saturation Voltage	$I_C = 10$ mA, $I_B = 1.0$ mA $I_C = 50$ mA, $I_B = 5.0$ mA		0.2 0.3	V V
$V_{BE(sat)}$	Base-Emitter Saturation Voltage	$I_C = 10$ mA, $I_B = 1.0$ mA $I_C = 50$ mA, $I_B = 5.0$ mA	0.65	0.85 0.95	V V
SMALL SIGNAL CHARACTERISTICS					
f_T	Current Gain - Bandwidth Product	$I_C = 10$ mA, $V_{CE} = 20$ V, f = 100 MHz	300		MHz
C_{obo}	Output Capacitance	$V_{CB} = 5.0$ V, $I_E = 0$, f = 1.0 MHz		4.0	pF
C_{ibo}	Input Capacitance	$V_{EB} = 0.5$ V, $I_C = 0$, f = 1.0 MHz		8.0	pF
NF	Noise Figure	$I_C = 100\ \mu A$, $V_{CE} = 5.0$ V, $R_S = 1.0 k\Omega$, f=10 Hz to 15.7kHz		5.0	dB
SWITCHING CHARACTERISTICS					
t_d	Delay Time	$V_{CC} = 3.0$ V, $V_{BE} = 0.5$ V,		35	ns
t_r	Rise Time	$I_C = 10$ mA, $I_{B1} = 1.0$ mA		35	ns
t_s	Storage Time	$V_{CC} = 3.0$ V, $I_C = 10$mA		200	ns
t_f	Fall Time	$I_{B1} = I_{B2} = 1.0$ mA		50	ns

*Pulse Test: Pulse Width ≤ 300 μs, Duty Cycle ≤ 2.0%

SECTION 4–3 CHECKUP

1. Define β_{DC} and α_{DC}. What is h_{FE}?
2. If the dc current gain of a transistor is 100, determine β_{DC} and α_{DC}.
3. What two variables are plotted on a collector characteristic curve?
4. What bias conditions must exist for a transistor to operate as an amplifier?
5. Does β_{DC} increase or decrease with temperature?
6. For a given type of transistor, can β_{DC} be considered to be a constant?

4–4 THE BJT AS AN AMPLIFIER

Amplification is the process of linearly increasing the amplitude of an electrical signal and is one of the major properties of a transistor. As you learned, a BJT exhibits current gain (called β). When a BJT is biased in the active (or linear) region, as previously described, the BE junction has a low resistance due to forward bias and the BC junction has a high resistance due to reverse bias.

After completing this section, you should be able to

- **Discuss how a BJT is used as a voltage amplifier**
- List the dc and ac quantities in an amplifier
  - Describe how the dc and ac quantities are identified
- Describe voltage amplification
  - Draw the schematic for a basic BJT amplifier ◆ Define *current gain* and *voltage gain* ◆ Calculate voltage gain ◆ Calculate amplifier output voltage

DC and AC Quantities

Before discussing the concept of transistor amplification, the designations that we will use for the circuit quantities of current, voltage, and resistance must be explained because amplifier circuits have both dc and ac quantities.

In this text, italic capital letters are used for both dc and ac currents (I) and voltages (V). This rule applies to rms, average, peak, and peak-to-peak ac values. AC current and voltage values are always rms unless stated otherwise. Although some texts use lowercase i and v for ac current and voltage, we reserve the use of lowercase i and v only for instantaneous values. In this text, the distinction between a dc current or voltage and an ac current or voltage is in the subscript.

DC quantities always carry an uppercase roman (nonitalic) subscript. For example, I_B, I_C, and I_E are the dc transistor currents. V_{BE}, V_{CB}, and V_{CE} are the dc voltages from one transistor terminal to another. Single subscripted voltages such as V_B, V_C, and V_E are dc voltages from the transistor terminals to ground.

AC and all time-varying quantities always carry a lowercase italic subscript. For example, I_b, I_c, and I_e are the ac transistor currents. V_{be}, V_{cb}, and V_{ce} are the ac voltages from one transistor terminal to another. Single subscripted voltages such as V_b, V_c, and V_e are ac voltages from the transistor terminals to ground.

The rule is different for *internal* transistor resistances. As you will see later, transistors have internal ac resistances that are designated by lowercase r' with an appropriate subscript. For example, the internal ac emitter resistance is designated as r'_e.

Circuit resistances external to the transistor itself use the standard italic capital R with a subscript that identifies the resistance as dc or ac (when applicable), just as for current and voltage. For example R_E is an external dc emitter resistance and R_e is an external ac emitter resistance.

Voltage Amplification

As you have learned, a transistor amplifies current because the collector current is equal to the base current multiplied by the current gain, β. The base current in a transistor is very small compared to the collector and emitter currents. Because of this, the collector current is approximately equal to the emitter current.

With this in mind, let's look at the circuit in Figure 4–21. An ac voltage, V_s, is superimposed on the dc bias voltage V_{BB} by capacitive coupling as shown. The dc bias voltage V_{CC} is connected to the collector through the collector resistor, R_C.

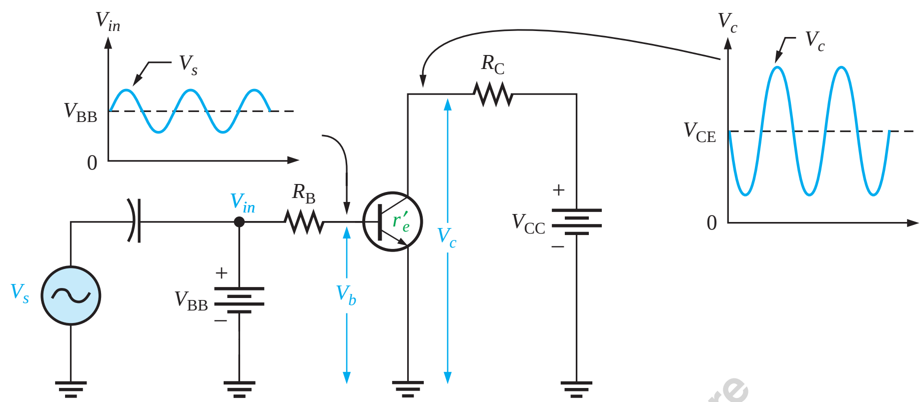


FIGURE 4–21

Basic transistor amplifier circuit with ac source voltage V_s and dc bias voltage V_{BB} superimposed.

The ac input voltage produces an ac base current, which results in a much larger ac collector current. The ac collector current produces an ac voltage across R_C, thus producing an amplified, but inverted, reproduction of the ac input voltage in the active region of operation, as illustrated in Figure 4–21.

The forward-biased base-emitter junction presents a very low resistance to the ac signal. This internal ac emitter resistance is designated r'_e in Figure 4–21 and appears in series with R_B. The ac base voltage is

$$V_b = I_e r'_e$$

The ac collector voltage, V_c, equals the ac voltage drop across R_C.

$$V_c = I_c R_C$$

Since $I_c \cong I_e$, the ac collector voltage is

$$V_c \cong I_e R_C$$

V_b can be considered the transistor ac input voltage where $V_b = V_s - I_b R_B$. V_c can be considered the transistor ac output voltage. Since *voltage gain* is defined as the ratio of the output voltage to the input voltage, the ratio of V_c to V_b is the ac voltage gain, A_v, of the transistor.

$$A_v = \frac{V_c}{V_b}$$

Substituting $I_e R_C$ for V_c and $I_e r'_e$ for V_b yields

$$A_v = \frac{V_c}{V_b} \cong \frac{I_e R_C}{I_e r'_e}$$

The I_e terms cancel; therefore,

$$\mathbf{A_v \cong \frac{R_C}{r'_e}} \qquad \text{Equation 4–7}$$

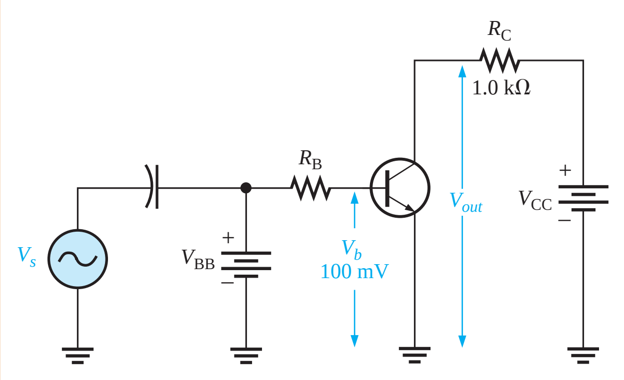
Equation 4–7 shows that the transistor in Figure 4–21 provides amplification in the form of voltage gain, which is dependent on the values of R_C and r'_e.

Since R_C is always considerably larger in value than r'_e, the output voltage for this configuration is greater than the input voltage. Various types of amplifiers are covered in detail in later chapters.

EXAMPLE 4–9

Determine the voltage gain and the ac output voltage in Figure 4–22 if $r'_e = 50\ \Omega$.

▶ FIGURE 4–22



Solution The voltage gain is

$$A_v \cong \frac{R_C}{r'_e} = \frac{1.0\ \text{k}\Omega}{50\ \Omega} = \mathbf{20}$$

Therefore, the ac output voltage is

$$V_{out} = A_v V_b = (20)(100\ \text{mV}) = \mathbf{2\ V\ rms}$$

Related Problem What value of R_C in Figure 4–22 will it take to have a voltage gain of 50?

SECTION 4–4 CHECKUP

1. What is amplification?
2. How is voltage gain defined?
3. Name two factors that determine the voltage gain of an amplifier.
4. What is the voltage gain of a transistor amplifier that has an output of 5 V rms and an input of 250 mV rms?
5. A transistor connected as in Figure 4–22 has an $r'_e = 20\ \Omega$. If R_C is 1200 Ω, what is the voltage gain?

4–5 The BJT as a Switch

In the previous section, you saw how a BJT can be used as a linear amplifier. The second major application area is switching applications. When used as an electronic switch, a BJT is normally operated alternately in cutoff and saturation. Many digital circuits use the BJT as a switch.

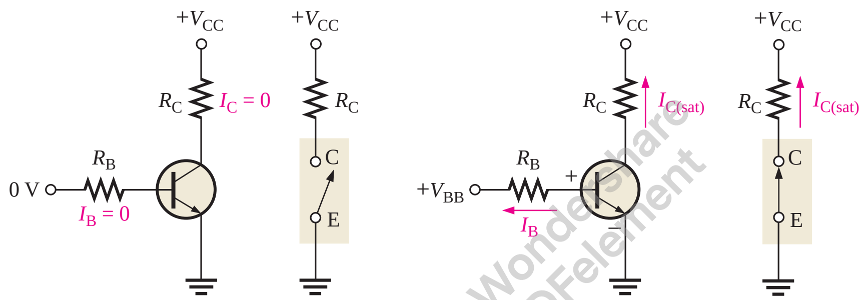
After completing this section, you should be able to

- **Discuss how a BJT is used as a switch**
- Describe BJT switching operation
- Explain the conditions in cutoff
  - Determine the cutoff voltage in terms of the dc supply voltage

- Explain the conditions in saturation
  - Calculate the collector current and the base current in saturation
- Describe a simple application

Switching Operation

Figure 4–23 illustrates the basic operation of a BJT as a switching device. In part (a), the transistor is in the cutoff region because the base-emitter junction is not forward-biased. In this condition, there is, ideally, an *open* between collector and emitter, as indicated by the switch equivalent. In part (b), the transistor is in the saturation region because the base-emitter junction and the base-collector junction are forward-biased and the base current is made large enough to cause the collector current to reach its saturation value. In this condition, there is, ideally, a *short* between collector and emitter, as indicated by the switch equivalent. Actually, a small voltage drop across the transister of up to a few tenths of a volt normally occurs, which is the saturation voltage, $V_{CE(sat)}$.



(a) Cutoff — open switch

(b) Saturation — closed switch

FIGURE 4–23

Switching action of an ideal transistor.

Conditions in Cutoff As mentioned before, a transistor is in the cutoff region when the base-emitter junction is not forward-biased. Neglecting leakage current, all of the currents are zero, and V_{CE} is equal to V_{CC}.

$$V_{CE(cutoff)} = V_{CC}$$ Equation 4–8

Conditions in Saturation As you have learned, when the base-emitter junction is forward-biased and there is enough base current to produce a maximum collector current, the transistor is saturated. The formula for collector saturation current is

$$I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C}$$ Equation 4–9

Since $V_{CE(sat)}$ is very small compared to V_{CC}, it can usually be neglected.

The minimum value of base current needed to produce saturation is

$$I_{B(min)} = \frac{I_{C(sat)}}{\beta_{DC}}$$ Equation 4–10

Normally, I_B should be significantly greater than $I_{B(min)}$ to ensure that the transistor is saturated.

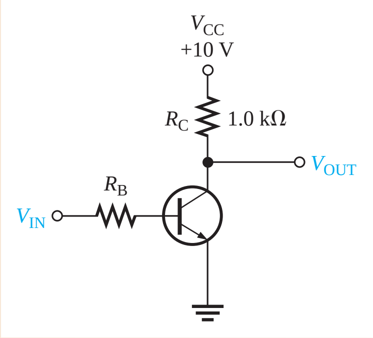
EXAMPLE 4–10

(a) For the transistor circuit in Figure 4–24, what is V_{CE} when $V_{IN} = 0$ V?

(b) What minimum value of I_B is required to saturate this transistor if β_{DC} is 200? Neglect $V_{CE(sat)}$.

(c) Calculate the maximum value of R_B when $V_{IN} = 5$ V.

▶ FIGURE 4–24



Solution **(a)** When $V_{IN} = 0$ V, the transistor is in cutoff (acts like an open switch) and

$$V_{CE} = V_{CC} = \mathbf{10\ V}$$

(b) Since $V_{CE(sat)}$ is neglected (assumed to be 0 V),

$$I_{C(sat)} = \frac{V_{CC}}{R_C} = \frac{10\text{ V}}{1.0\text{ k}\Omega} = 10\text{ mA}$$

$$I_{B(min)} = \frac{I_{C(sat)}}{\beta_{DC}} = \frac{10\text{ mA}}{200} = \mathbf{50\ \mu A}$$

This is the value of I_B necessary to drive the transistor to the point of saturation. Any further increase in I_B will ensure the transistor remains in saturation but there cannot be any further increase in I_C.

(c) When the transistor is on, $V_{BE} \cong 0.7$ V. The voltage across R_B is

$$V_{R_B} = V_{IN} - V_{BE} \cong 5\text{ V} - 0.7\text{ V} = 4.3\text{ V}$$

Calculate the maximum value of R_B needed to allow a minimum I_B of 50 μA using Ohm's law as follows:

$$R_{B(max)} = \frac{V_{R_B}}{I_{B(min)}} = \frac{4.3\text{ V}}{50\ \mu\text{A}} = \mathbf{86\ k\Omega}$$

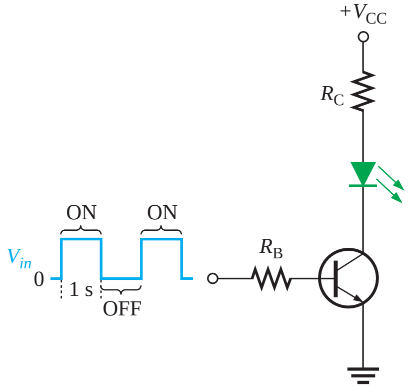
Related Problem Determine the minimum value of I_B required to saturate the transistor in Figure 4–24 if β_{DC} is 125 and $V_{CE(sat)}$ is 0.2 V.

A Simple Application of a Transistor Switch

The transistor in Figure 4–25 is used as a switch to turn the LED on and off. For example, a square wave input voltage with a period of 2 s is applied to the input as indicated. When

▶ FIGURE 4–25

A transistor used to switch an LED on and off.



the square wave is at 0 V, the transistor is in cutoff; and since there is no collector current, the LED does not emit light. When the square wave goes to its high level, the transistor saturates. This forward-biases the LED, and the resulting collector current through the LED causes it to emit light. Thus, the LED is on for 1 second and off for 1 second.

EXAMPLE 4–11

The LED in Figure 4–25 requires 30 mA to emit a sufficient level of light. Therefore, the collector current should be approximately 30 mA. For the following circuit values, determine the amplitude of the square wave input voltage necessary to make sure that the transistor saturates. Use double the minimum value of base current as a safety margin to ensure saturation. $V_{CC} = 9\text{ V}$, $V_{CE(sat)} = 0.3\text{ V}$, $R_C = 220\ \Omega$, $R_B = 3.3\text{ k}\Omega$, $\beta_{DC} = 50$, and $V_{LED} = 1.6\text{ V}$.

Solution

$$I_{C(sat)} = \frac{V_{CC} - V_{LED} - V_{CE(sat)}}{R_C} = \frac{9\text{ V} - 1.6\text{ V} - 0.3\text{ V}}{220\ \Omega} = 32.3\text{ mA}$$

$$I_{B(min)} = \frac{I_{C(sat)}}{\beta_{DC}} = \frac{32.3\text{ mA}}{50} = 646\ \mu\text{A}$$

To ensure saturation, use twice the value of $I_{B(min)}$, which is 1.29 mA. Use Ohm's law to solve for V_{in}.

$$I_B = \frac{V_{R_B}}{R_B} = \frac{V_{in} - V_{BE}}{R_B} = \frac{V_{in} - 0.7\text{ V}}{3.3\text{ k}\Omega}$$

$$V_{in} - 0.7\text{ V} = 2I_{B(min)}R_B = (1.29\text{ mA})(3.3\text{ k}\Omega)$$

$$V_{in} = (1.29\text{ mA})(3.3\text{ k}\Omega) + 0.7\text{ V} = \mathbf{4.96\text{ V}}$$

Related Problem

If you change the LED in Figure 4–25 to one that requires 50 mA for a specified light emission and you can't increase the input amplitude above 5 V or V_{CC} above 9 V, how would you modify the circuit? Specify the component(s) to be changed and the value(s).

Open the Multisim file E04-11 in the Examples folder on the companion website. Using a 0.5 Hz square wave input with the calculated amplitude, verify that the transistor is switching between cutoff and saturation and that the LED is alternately turning on and off.

SECTION 4–5 CHECKUP

1. When a transistor is used as a switch, in what two states is it operated?
2. When is the collector current maximum?
3. When is the collector current approximately zero?
4. Under what condition is $V_{CE} = V_{CC}$?
5. When is V_{CE} minimum?

4–6 THE PHOTOTRANSISTOR

A phototransistor is similar to a regular BJT except that the base current is produced and controlled by light instead of a voltage source. The phototransistor effectively converts light energy to an electrical signal.

After completing this section, you should be able to

- **Discuss the phototransistor and its operation**
  - Identify the schematic symbol ◆ Calculate the collector current ◆ Interpret a set of collector characteristic curves
- Describe a simple application
- Discuss optocouplers
  - Define *current transfer ratio* ◆ Give examples of how optocouplers are used

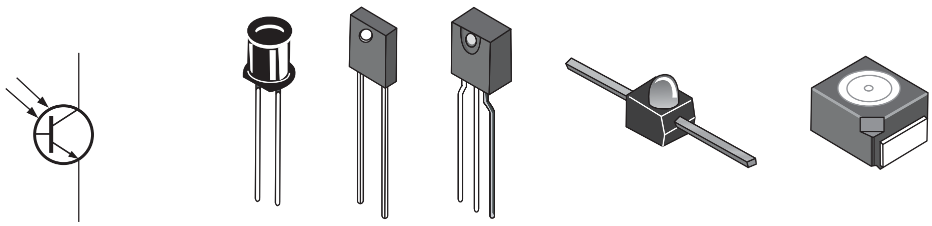
In a **phototransistor** the base current is produced when light strikes the photosensitive semiconductor base region. The collector-base *pn* junction is exposed to incident light through a lens opening in the transistor package. When there is no incident light, there is only a small thermally generated collector-to-emitter leakage current, I_{CEO}; this dark current is typically in the nA range. When light strikes the collector-base *pn* junction, a base current, I_λ, is produced that is directly proportional to the light intensity. This action produces a collector current that increases with I_λ. Except for the way base current is generated, the phototransistor behaves as a conventional BJT. In many cases, there is no electrical connection to the base.

The relationship between the collector current and the light-generated base current in a phototransistor is

Equation 4–11

$$I_C = \beta_{DC} I_\lambda$$

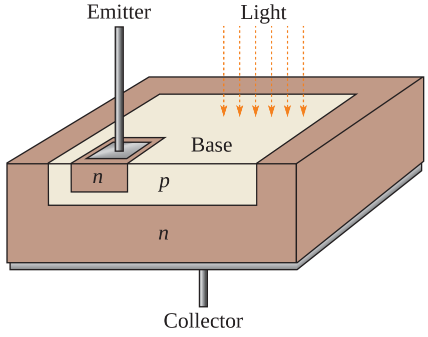
The schematic symbol and some typical phototransistors are shown in Figure 4–26. Since the actual photogeneration of base current occurs in the collector-base region, the larger the physical area of this region, the more base current is generated. Thus, a typical phototransistor is designed to offer a large area to the incident light, as the simplified structure diagram in Figure 4–27 illustrates.



(a) Schematic symbol (b) Typical packages

▶ FIGURE 4–26

Phototransistor.



▶ FIGURE 4–27

Typical phototransistor structure.

A phototransistor can be either a two-lead or a three-lead device. In the three-lead configuration, the base lead is brought out so that the device can be used as a conventional BJT with or without the additional light-sensitivity feature. In the two-lead configuration, the base is not electrically available, and the device can be used only with light as the input. In many applications, the phototransistor is used in the two-lead version.

Figure 4–28 shows a phototransistor with a biasing circuit and typical collector characteristic curves. Notice that each individual curve on the graph corresponds to a certain value of light intensity (in this case, the units are mW/cm^2) and that the collector current in creases with light intensity.

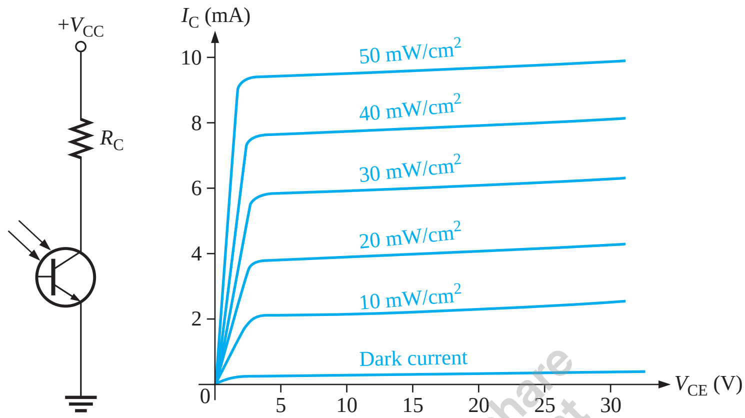


FIGURE 4–28

Phototransistor circuit and typical collector characteristic curves.

Phototransistors are not sensitive to all light but only to light within a certain range of wavelengths. They are most sensitive to particular wavelengths in the red and infrared part of the spectrum, as shown by the peak of the infrared spectral response curve in Figure 4–29.

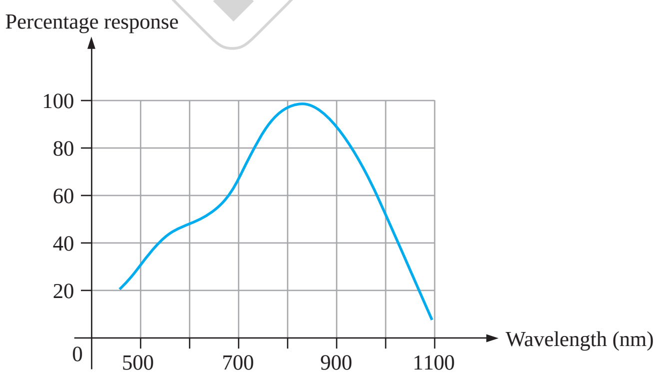


FIGURE 4–29

Typical phototransistor spectral response.

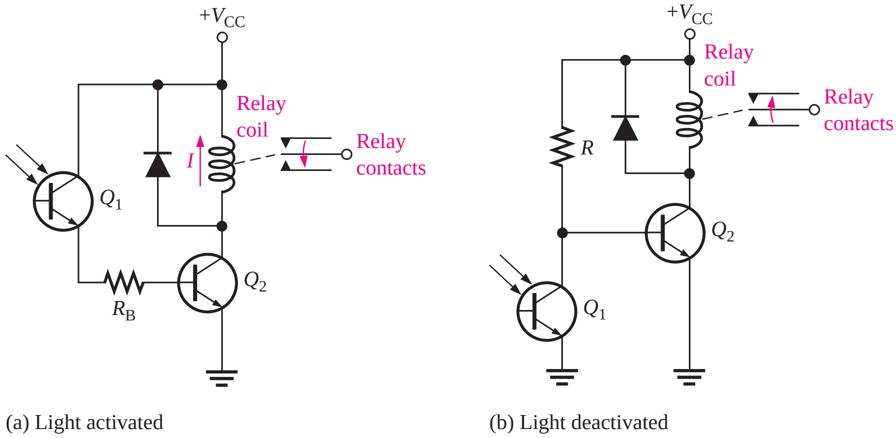
Applications

Phototransistors are used in a variety of applications. A light-operated relay circuit is shown in Figure 4–30(a). The phototransistor Q_1 drives the BJT Q_2. When there is sufficient incident light on Q_1, transistor Q_2 is driven into saturation, and collector current through the relay coil energizes the relay. The diode across the relay coil prevents, by its limiting action, a large voltage transient from occurring at the collector of Q_2 when the transistor turns off.

Figure 4–30(b) shows a circuit in which a relay is deactivated by incident light on the phototransistor. When there is insufficient light, transistor Q_2 is biased on, keeping the relay energized. When there is sufficient light, phototransistor Q_1 turns on; this pulls the base of Q_2 low, thus turning Q_2 off and de-energizing the relay.

▶ **FIGURE 4–30**

Relay circuits driven by a phototransistor.

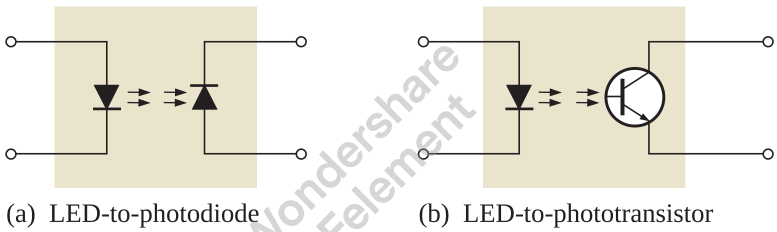


Optocouplers

An **optocoupler** uses an LED optically coupled to a photodiode or a phototransistor in a single package. Two basic types are LED-to-photodiode and LED-to-phototransistor, as shown in Figure 4–31. Examples of typical packages are shown in Figure 4–32.

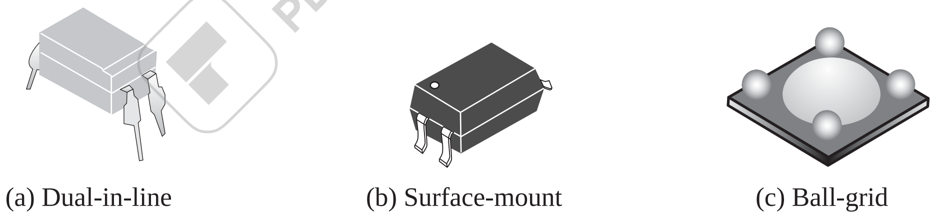
▶ **FIGURE 4–31**

Basic optocouplers.



▶ **FIGURE 4–32**

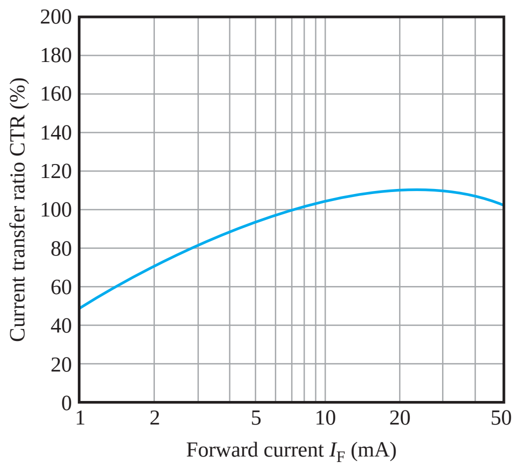
Examples of optocoupler packages.



A key parameter in optocouplers is the **CTR** (current transfer ratio). The CTR is an indication of how efficiently a signal is coupled from input to output and is expressed as the ratio of a change in the LED current to the corresponding change in the photodiode or phototransistor current. It is usually expressed as a percentage. Figure 4–33 shows a

▶ **FIGURE 4–33**

CTR versus I_F for a typical optocoupler.



typical graph of CTR versus forward LED current. For this case, it varies from about 50% to about 110%.

Optocouplers are used to isolate sections of a circuit that are incompatible in terms of the voltage levels or currents required. For example, they are used to protect hospital patients from shock when they are connected to monitoring instruments or other devices. They are also used to isolate low-current control or signal circuits from noisy power supply circuits or higher-current motor and machine circuits.

SECTION 4–6 CHECKUP

1. How does a phototransistor differ from a conventional BJT?
2. A three-lead phototransistor has an external (emitter, base, collector) lead.
3. The collector current in a phototransistor circuit depends on what two factors?
4. What is the optocoupler parameter, OTR?

4–7 TRANSISTOR CATEGORIES AND PACKAGING

BJTs are available in a wide range of package types for various applications. Those with mounting studs or heat sinks are usually power transistors. Low-power and medium-power transistors are usually found in smaller metal or plastic cases. Still another package classification is for high-frequency devices. You should be familiar with common transistor packages and be able to identify the emitter, base, and collector terminals.

After completing this section, you should be able to

- **Identify various types of transistor packages**
- List three broad transistor categories
  - Identify package pin configurations

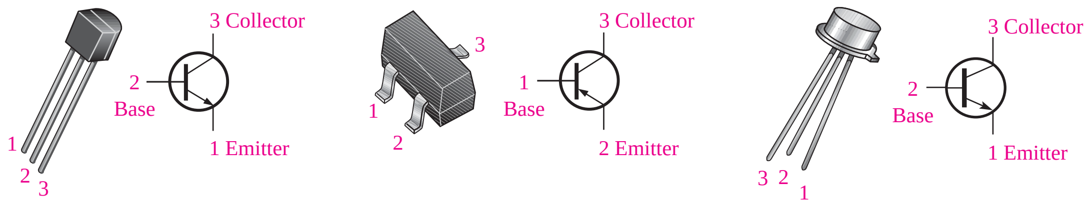
Transistor Categories

Manufacturers generally classify bipolar junction transistors into three broad categories: general-purpose/small-signal devices, power devices, and RF (radio frequency/microwave) devices. Although each of these categories, to a large degree, has its own unique package types, you will find certain types of packages used in more than one device category. Let's look at transistor packages for each of the three categories so that you will be able to recognize a transistor when you see one on a circuit board and have a good idea of what general category it is in.

General-Purpose/Small-Signal Transistors General-purpose/small-signal transistors are generally used for low- or medium-power amplifiers or switching circuits. The packages are either plastic or metal cases. Certain types of packages contain multiple transistors. Figure 4–34 illustrates two common plastic cases and a metal can package.

Figure 4–35 shows multiple-transistor packages. Some of the multiple-transistor packages such as the dual in-line (DIP) and the small-outline (SO) are the same as those used for many integrated circuits. Typical pin connections are shown so you can identify the emitter, base, and collector.

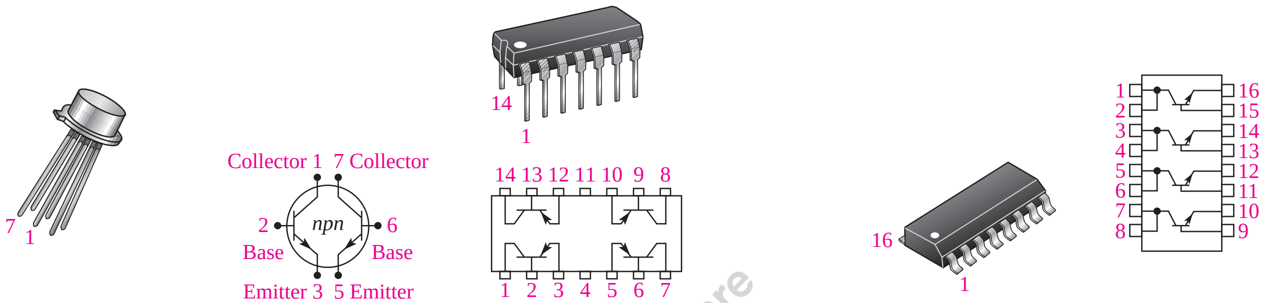
Power Transistors Power transistors are used to handle large currents (typically more than 1 A) and/or large voltages. For example, the final audio stage in a stereo system uses a power transistor amplifier to drive the speakers. Figure 4–36 shows some common package



(a) TO-92 (b) SOT-23 (c) TO-18. Emitter is closest to tab.

▲ **FIGURE 4–34**

Plastic and metal cases for general-purpose/small-signal transistors. Pin configurations may vary. Always check the datasheet (*http://fairchildsemiconductor.com/*).



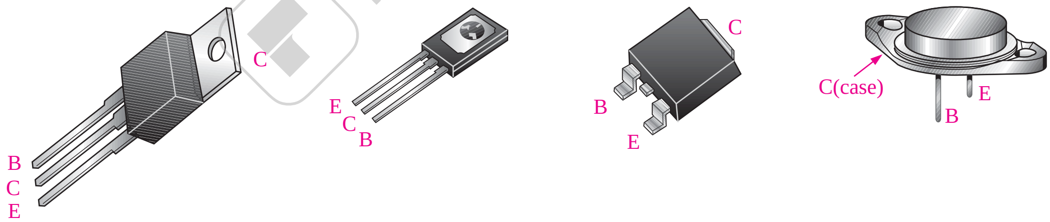
(a) Dual metal can. Emitters are closest to tab.

(b) Quad dual in-line (DIP) and quad flat-pack. Dot indicates pin 1.

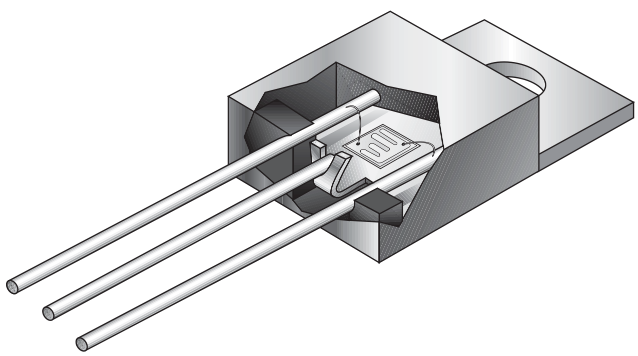
(c) Quad small outline (SO) package for surface-mount technology

▲ **FIGURE 4–35**

Examples of multiple-transistor packages.



(a) TO-220 (b) TO-225 (c) D-Pack (d) TO-3



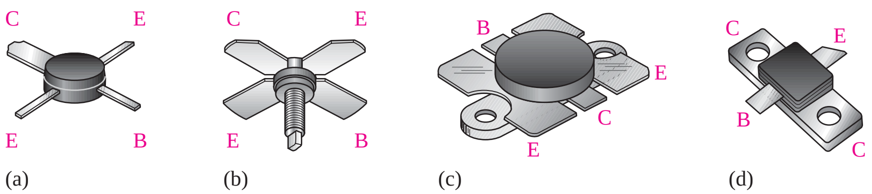
(e) Greatly enlarged cutaway view of tiny transistor chip mounted in the encapsulated package

▲ **FIGURE 4–36**

Examples of power transistors and packages.

configurations. The metal tab or the metal case is common to the collector and is thermally connected to a heat sink for heat dissipation. Notice in part (e) how the small transistor chip is mounted inside the much larger package.

RF Transistors RF transistors are designed to operate at extremely high frequencies and are commonly used for various purposes in communications systems and other high-frequency applications. Their unusual shapes and lead configurations are designed to optimize certain high-frequency parameters. Figure 4–37 shows some examples.



▲ FIGURE 4–37

Examples of RF transistor packages.

SECTION 4–7 CHECKUP

1. List the three broad categories of bipolar junction transistors.
2. In a metal can package of a general-purpose BJT, how is the emitter identified?
3. In power transistors, the metal mounting tab or case is connected to which transistor region?

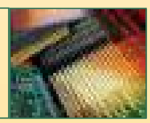
4–8 TROUBLESHOOTING

As you already know, a critical skill in electronics work is the ability to identify a circuit malfunction and to isolate the failure to a single component if necessary. In this section, the basics of troubleshooting transistor bias circuits and testing individual transistors are covered.

After completing this section, you should be able to

- **Troubleshoot faults in transistor circuits**
- Troubleshoot a biased transistor
  - Calculate what the readings should be
  - Define *floating point*
- Test a transistor using a DMM
  - Discuss the DMM diode test position
  - Describe testing using the OHMs function
- Describe the transistor tester
- Discuss in-circuit and out-of-circuit testing
  - Explain point-of-measurement troubleshooting
  - Describe leakage measurement and gain measurement
- Explain what a curve tracer is

Chapter 18 Basic Programming Concepts for Automated Testing
Selected sections from Chapter 18 may be introduced as part of this troubleshooting coverage or, optionally, the entire Chapter 18 may be covered later or not at all.



Troubleshooting a Biased Transistor

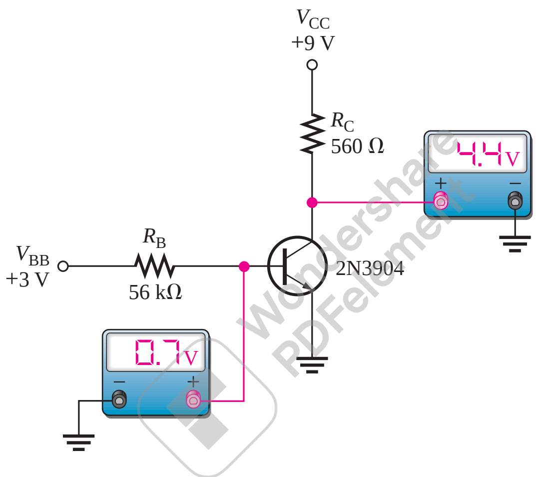
Several faults can occur in a simple transistor bias circuit. Possible faults are open bias resistors, open or resistive connections, shorted connections, and opens or shorts internal to the transistor itself. Figure 4–38 is a basic transistor bias circuit with all voltages referenced to ground. The two bias voltages are $V_{BB} = 3$ V and $V_{CC} = 9$ V. The correct voltage measurements at the base and collector are shown. Analytically, these voltages are verified as follows. A $\beta_{DC} = 200$ is taken as midway between the minimum and maximum values of h_{FE} given on the datasheet for the 2N3904 in Figure 4–20. A different h_{FE} (β_{DC}), of course, will produce different results for the given circuit.

$$V_B = V_{BE} = 0.7\text{ V}$$

$$I_B = \frac{V_{BB} - 0.7\text{ V}}{R_B} = \frac{3\text{ V} - 0.7\text{ V}}{56\text{ k}\Omega} = \frac{2.3\text{ V}}{56\text{ k}\Omega} = 41.1\ \mu\text{A}$$

$$I_C = \beta_{DC} I_B = 200(41.1\ \mu\text{A}) = 8.2\text{ mA}$$

$$V_C = 9\text{ V} - I_C R_C = 9\text{ V} - (8.2\text{ mA})(560\ \Omega) = 4.4\text{ V}$$



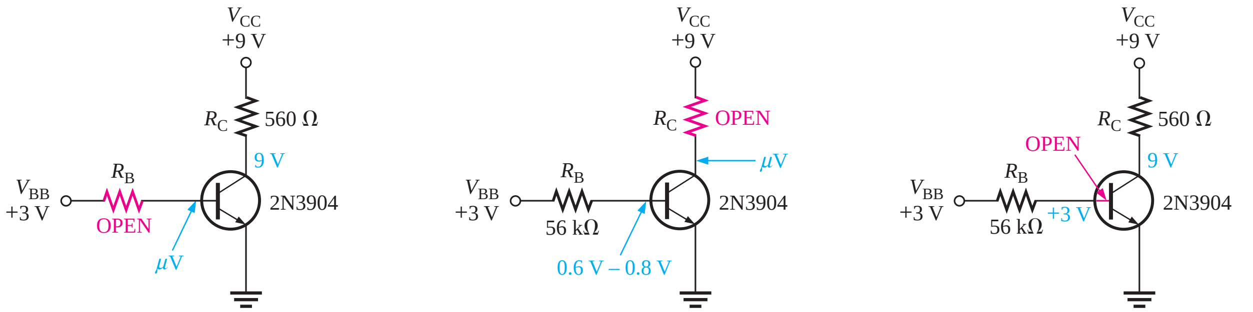
▲ **FIGURE 4–38**

A basic transistor bias circuit.

Several faults that can occur in the circuit and the accompanying symptoms are illustrated in Figure 4–39. Symptoms are shown in terms of measured voltages that are incorrect. If a transistor circuit is not operating correctly, it is a good idea to verify that V_{CC} and ground are connected and operating. A simple check at the top of the collector resistor and at the collector itself will quickly ascertain if V_{CC} is present and if the transistor is conducting normally or is in cutoff or saturation. If it is in cutoff, the collector voltage will equal V_{CC}; if it is in saturation, the collector voltage will be near zero. Another faulty measurement can be seen if there is an open in the collector path. The term **floating point** refers to a point in the circuit that is not electrically connected to ground or a "solid" voltage. Normally, very small and sometimes fluctuating voltages in the μV to low mV range are generally measured at floating points. The faults in Figure 4–39 are typical but do not represent all possible faults that may occur.

Testing a Transistor with a DMM

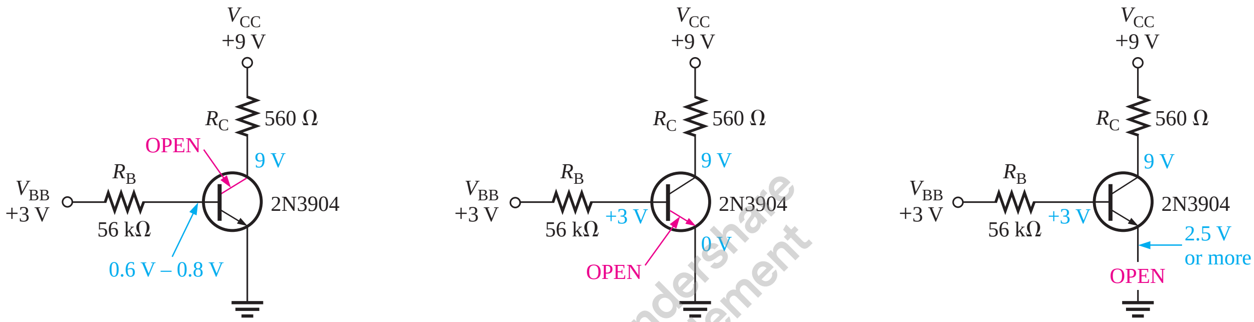
A digital multimeter can be used as a fast and simple way to check a transistor for open or shorted junctions. For this test, you can view the transistor as two diodes connected as shown in Figure 4–40 for both *npn* and *pnp* transistors. The base-collector junction is one diode and the base-emitter junction is the other.



(a) ***Fault:*** Open base resistor.
Symptoms: Readings from μV to a few mV at base due to floating point. 9 V at collector because transistor is in cutoff.

(b) ***Fault:*** Open collector resistor.
Symptoms: A very small voltage may be observed at the collector when a meter is connected due to the current path through the BC junction and the meter resistance.

(c) ***Fault:*** Base internally open.
Symptoms: 3 V at base lead. 9 V at collector because transistor is in cutoff.



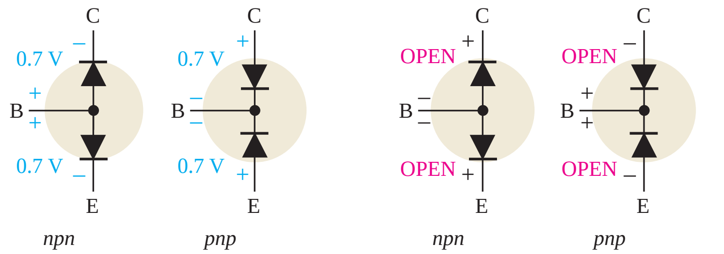
(d) ***Fault:*** Collector internally open.
Symptoms: 0.6 V – 0.8 V at base lead due to forward voltage drop across base-emitter junction. 9 V at collector because the open prevents collector current.

(e) ***Fault:*** Emitter internally open.
Symptoms: 3 V at base lead. 9 V at collector because there is no collector current. 0 V at the emitter as normal.

(f) ***Fault:*** Open ground connection.
Symptoms: 3 V at base lead. 9 V at collector because there is no collector current. 2.5 V or more at the emitter due to the forward voltage drop across the base-emitter junction. The measuring voltmeter provides a forward current path through its internal resistance.

▲ **FIGURE 4–39**

Examples of faults and symptoms in the basic transistor bias circuit.



(a) Both junctions should typically read 0.7 V when forward-biased.

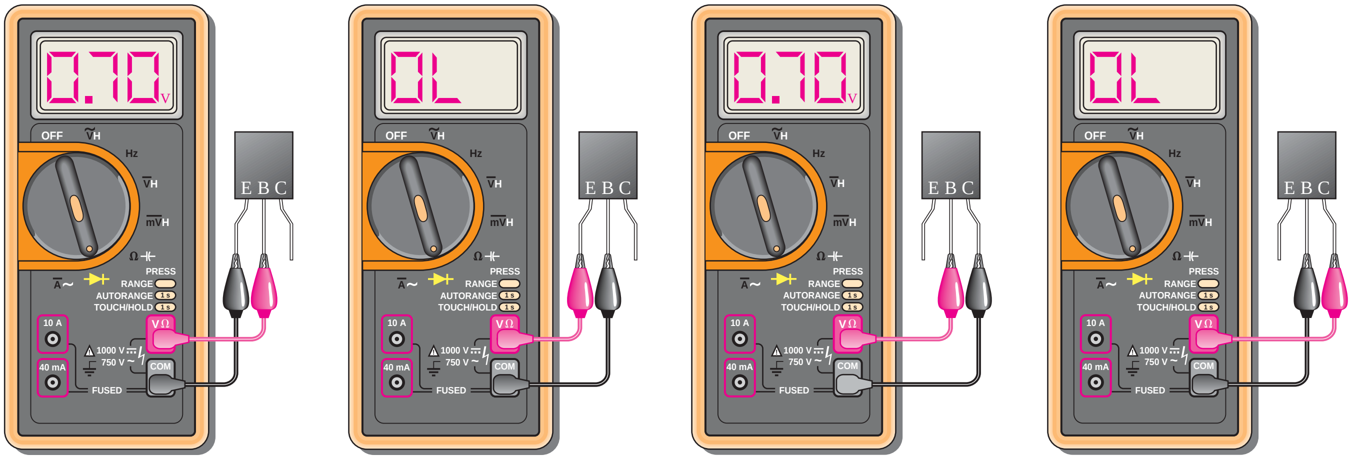
(b) Both junctions should ideally read OPEN when reverse-biased.

◀ **FIGURE 4–40**

A transistor viewed as two diodes.

Recall that a good diode will show an extremely high resistance (or open) with reverse bias and a very low resistance with forward bias. A defective open diode will show an extremely high resistance (or open) for both forward and reverse bias. A defective shorted or resistive diode will show zero or a very low resistance for both forward and reverse bias. An open diode is the most common type of failure. Since the transistor *pn* junctions are, in effect diodes, the same basic characteristics apply.

The DMM Diode Test Position Many digital multimeters (DMMs) have a *diode test* position that provides a convenient way to test a transistor. A typical DMM, as shown in Figure 4–41, has a small diode symbol to mark the position of the function switch. When set to diode test, the meter provides an internal voltage sufficient to forward-bias and reverse-bias a transistor junction.



(a) Forward-bias test of the BE junction

(b) Reverse-bias test of the BE junction

(c) Forward-bias test of the BC junction

(d) Reverse-bias test of the BC junction

▲ **FIGURE 4–41**

Typical DMM test of a properly functioning *npn* transistor. Leads are reversed for a *pnp* transistor.

When the Transistor Is Not Defective In Figure 4–41(a), the red (positive) lead of the meter is connected to the base of an *npn* transistor and the black (negative) lead is connected to the emitter to forward-bias the base-emitter junction. If the junction is good, you will get a reading of between approximately 0.6 V and 0.8 V, with 0.7 V being typical for forward bias.

In Figure 4–41(b), the leads are switched to reverse-bias the base-emitter junction, as shown. If the transistor is working properly, you will typically get an OL indication.

The process just described is repeated for the base-collector junction as shown in Figure 4–41(c) and (d). For a *pnp* transistor, the polarity of the meter leads are reversed for each test.

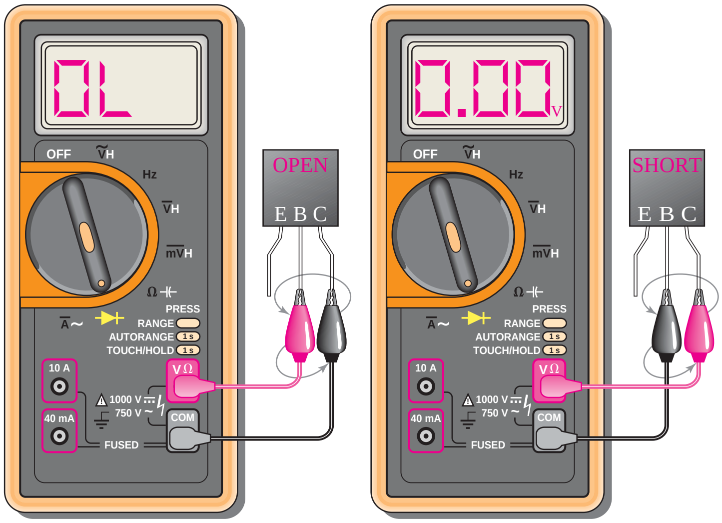
When the Transistor Is Defective When a transistor has failed with an open junction or internal connection, you get an open circuit voltage reading (OL) for both the forward-bias and the reverse-bias conditions for that junction, as illustrated in Figure 4–42(a). If a junction is shorted, the meter reads 0 V in both forward- and reverse-bias tests, as indicated in part (b).

Some DMMs provide a test socket on their front panel for testing a transistor for the h_{FE} (β_{DC}) value. If the transistor is inserted improperly in the socket or if it is not functioning properly due to a faulty junction or internal connection, a typical meter will flash a 1 or display a 0. If a value of β_{DC} within the normal range for the specific transistor is displayed, the device is functioning properly. The normal range of β_{DC} can be determined from the datasheet.

Checking a Transistor with the OHMs Function DMMs that do not have a diode test position or an h_{FE} socket can be used to test a transistor for open or shorted junctions by setting the function switch to an OHMs range. For the forward-bias check of a good transistor *pn* junction, you will get a resistance reading that can vary depending on the meter's internal battery. Many DMMs do not have sufficient voltage on the OHMs range to fully forward-bias a junction, and you may get a reading of from several hundred to several thousand ohms.

For the reverse-bias check of a good transistor, you will get an out-of-range indication on most DMMs because the reverse resistance is too high to measure. An out-of-range indication may be a flashing 1 or a display of dashes, depending on the particular DMM.

Even though you may not get accurate forward and reverse resistance readings on a DMM, the relative readings are sufficient to indicate a properly functioning transistor *pn* junction. The out-of-range indication shows that the reverse resistance is very high, as you



(a) Forward-bias test and reverse-bias test give the same reading (OL is typical) for an open BC junction.

(b) Forward- and reverse-bias tests for a shorted junction give the same 0 V reading.

◄ **FIGURE 4–42**

Testing a defective *npn* transistor. Leads are reversed for a *pnp* transistor.

expect. The reading of a few hundred to a few thousand ohms for forward bias indicates that the forward resistance is small compared to the reverse resistance, as you expect.

Transistor Testers

An individual transistor can be tested either in-circuit or out-of-circuit with a transistor tester. For example, let's say that an amplifier on a particular printed circuit (PC) board has malfunctioned. Good troubleshooting practice dictates that you do not unsolder a component from a circuit board unless you are reasonably sure that it is bad or you simply cannot isolate the problem down to a single component. When components are removed, there is a risk of damage to the PC board contacts and traces.

You can perform an in-circuit check of the transistor using a transistor tester similar to the one shown in Figure 4–43. The three clip-leads are connected to the transistor terminals and the tester gives a positive indication if the transistor is good.

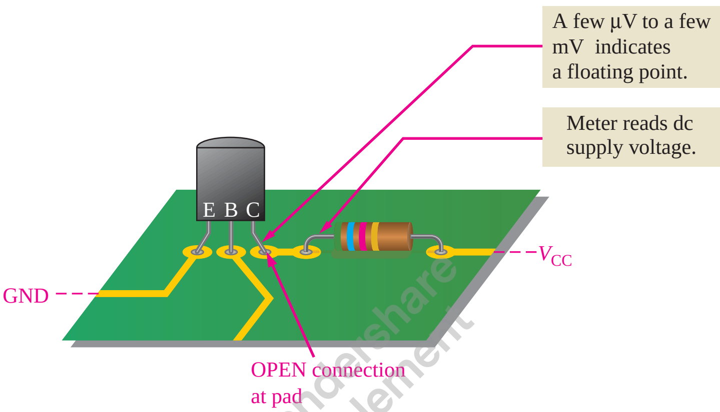
◄ **FIGURE 4–43**

Transistor tester (courtesy of B + K Precision).

In-Circuit and Out-of-Circuit Tests

Case 1 If the transistor tests defective, it should be carefully removed and replaced with a known good one. An out-of-circuit check of the replacement device is usually a good idea, just to make sure it is OK. The transistor is plugged into the socket on the transistor tester for out-of-circuit tests.

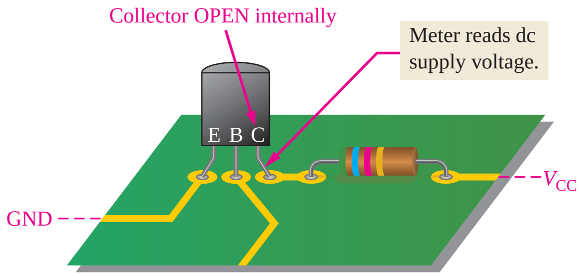
Case 2 If the transistor tests good in-circuit but the circuit is not working properly, examine the circuit board for a poor connection at the collector pad or for a break in the connecting trace. A poor solder joint often results in an open or a highly resistive contact. The physical point at which you actually measure the voltage is very important in this case. For example, if you measure on the collector lead when there is an external open at the collector pad, you will measure a floating point. If you measure on the connecting trace or on the R_C lead, you will read V_{CC}. This situation is illustrated in Figure 4–44.



▶ FIGURE 4–44

The indication of an open, when it is in the circuit external to the transistor, depends on where you measure.

Importance of Point-of-Measurement in Troubleshooting In case 2, if you had taken the initial measurement on the transistor lead itself and the open were *internal* to the transistor as shown in Figure 4–45, you would have measured V_{CC}. This indicates a defective transistor even before the tester was used, assuming the base-to-emitter voltage is normal. This simple concept emphasizes the importance of point-of-measurement in certain troubleshooting situations.



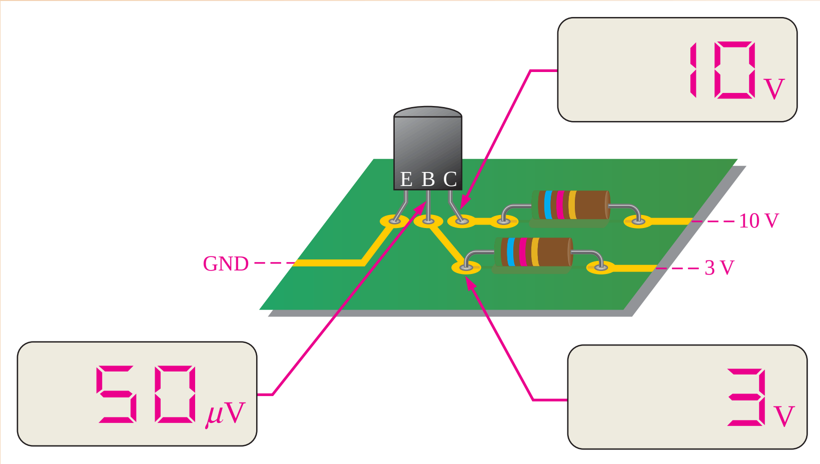
▶ FIGURE 4–45

Illustration of an internal open. Compare with Figure 4–44.

EXAMPLE 4–12 What fault do the measurements in Figure 4–46 indicate?

Solution The transistor is in cutoff, as indicated by the 10 V measurement on the collector lead. The base bias voltage of 3 V appears on the PC board contact but not on the transistor lead, as indicated by the floating point measurement. This shows that there is an open external to the transistor between the two measured base points. Check the solder joint at the base contact on the PC board. If the open were internal, there would be 3 V on the base lead.

Related Problem If the meter in Figure 4–46 that now reads 3 V indicates a floating point when touching the circuit board pad, what is the most likely fault?



◀ FIGURE 4–46

Leakage Measurement Very small leakage currents exist in all transistors and in most cases are small enough to neglect (usually nA). When a transistor is connected with the base open ($I_B = 0$), it is in cutoff. Ideally $I_C = 0$; but actually there is a small current from collector to emitter, as mentioned earlier, called I_{CEO} (collector-to-emitter current with base open). This leakage current is usually in the nA range. A faulty transistor will often have excessive leakage current and can be checked in a transistor tester. Another leakage current in transistors is the reverse collector-to-base current, I_{CBO}. This is measured with the emitter open. If it is excessive, a shorted collector-base junction is likely.

Gain Measurement In addition to leakage tests, the typical transistor tester also checks the β_{DC}. A known value of I_B is applied, and the resulting I_C is measured. The reading will indicate the value of the I_C/I_B ratio, although in some units only a relative indication is given. Most testers provide for an in-circuit β_{DC} check, so that a suspected device does not have to be removed from the circuit for testing.

Curve Tracers A *curve tracer* is an oscilloscope type of instrument that can display transistor characteristics such as a family of collector curves. In addition to the measurement and display of various transistor characteristics, diode curves can also be displayed.

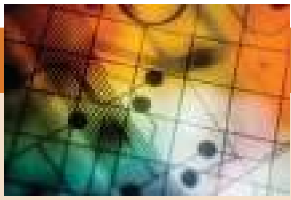
Multisim Troubleshooting Exercises

These file circuits are in the Troubleshooting Exercises folder on the companion website. Open each file and determine if the circuit is working properly. If it is not working properly, determine the fault.

1. Multisim file TSE04-01
2. Multisim file TSE04-02
3. Multisim file TSE04-03
4. Multisim file TSE04-04

SECTION 4–8 CHECKUP

1. If a transistor on a circuit board is suspected of being faulty, what should you do?
2. In a transistor bias circuit, such as the one in Figure 4–38; what happens if R_B opens?
3. In a circuit such as the one in Figure 4–38, what are the base and collector voltages if there is an external open between the emitter and ground?



Application Activity: *Security Alarm System*

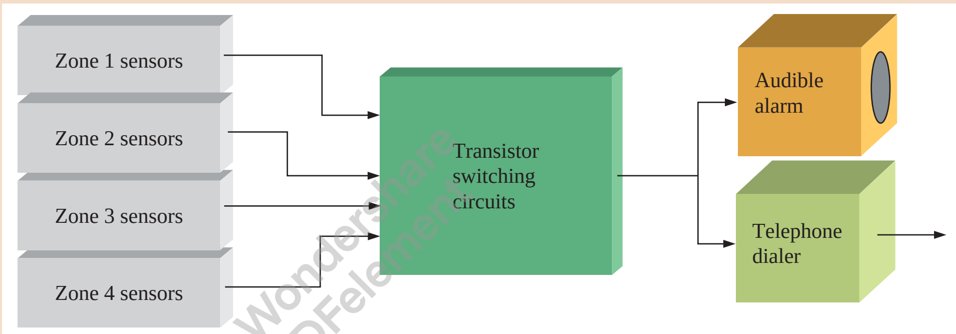
A circuit using transistor switches will be developed for use in an alarm system for detecting forced entry into a building. In its simplest form, the alarm system will accommodate four zones with any number of openings. It can be expanded to cover additional zones. For the purposes of this application, a zone is one room in a house or other building. The sensor used for each opening can be either a mechanical switch, a magnetically operated switch, or an optical sensor. Detection of an intrusion can be used to initiate an audible alarm signal and/or to initiate transmission of a signal over the phone line to a monitoring service.

Designing the Circuit

A basic block diagram of the system is shown in Figure 4–47. The sensors for each zone are connected to the switching circuits, and the output of the switching circuit goes to an audible alarm circuit and/or to a telephone dialing circuit. The focus of this application is the transistor switching circuits.

▶ **FIGURE 4–47**

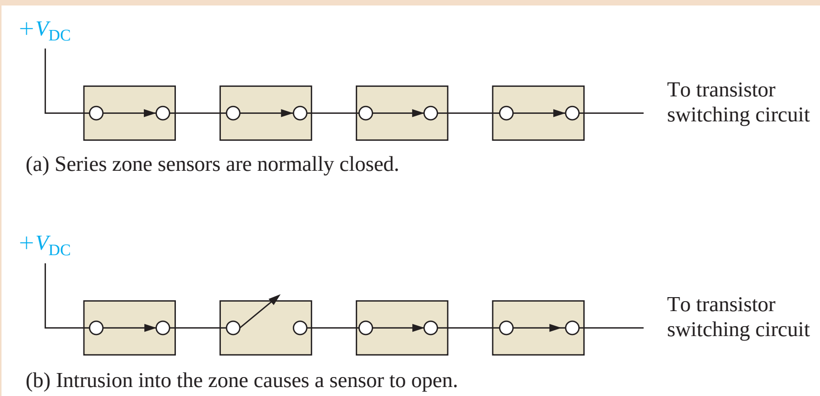
Block diagram of security alarm system.



A zone sensor detects when a window or door is opened. They are normally in a closed position and are connected in series to a dc voltage source, as shown in Figure 4–48(a). When a window or door is opened, the corresponding sensor creates an open circuit, as shown in part (b). The sensors are represented by switch symbols.

▶ **FIGURE 4–48**

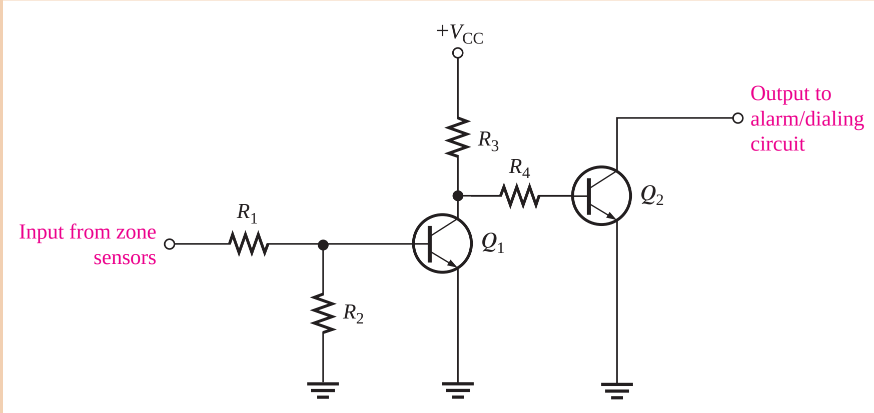
Zone sensor configuration.



A circuit for one zone is shown in Figure 4–49. It consists of two BJTs, Q_1 and Q_2. As long as the zone sensors are closed, Q_1 is in the *on* state (saturated). The very low saturation voltage at the Q_1 collector keeps Q_2 *off*. Notice that the collector of Q_2 is left open with no load connected. This allows for all four of the zone circuit outputs to be tied together and a common load connected externally to drive the alarm and/or dialing circuits. If one of the zone sensors opens, indicating a break-in, Q_1 turns *off* and its collector voltage goes to V_{CC}. This turns on Q_2, causing it to saturate. The *on* state of Q_2 will then activate the audible alarm and the telephone dialing sequence.

▶ **FIGURE 4–49**

One of the four identical transistor switching circuits.



1. Refer to the partial datasheet for the 2N2222A in Figure 4–50 and determine the value of the collector resistor R_3 to limit the current to 10 mA with a +12 V dc supply voltage.

Absolute Maximum Ratings * T_a=25°C unless otherwise noted

Symbol	Parameter	Value	Units
V_{CEO}	Collector-Emitter Voltage	40	V
V_{CBO}	Collector-Base Voltage	75	V
V_{EBO}	Emitter-Base Voltage	6.0	V
I_C	Collector Current	1.0	A
T_{STG}	Operating and Storage Junction Temperature Range	- 55 ~ 150	°C

* These ratings are limiting values above which the serviceability of any semiconductor device may be impaired

NOTES:
1) These ratings are based on a maximum junction temperature of 150 degrees C.
2) These are steady state limits. The factory should be consulted on applications involving pulsed or low duty cycle operations

Electrical Characteristics T_a=25°C unless otherwise noted

Symbol	Parameter	Test Condition	Min.	Max.	Units
Off Characteristics					
$BV_{(BR)CEO}$	Collector-Emitter Breakdown Voltage *	I_C = 10mA, I_B = 0	40		V
$BV_{(BR)CBO}$	Collector-Base Breakdown Voltage	I_C = 10μA, I_E = 0	75		V
$BV_{(BR)EBO}$	Emitter-Base Breakdown Voltage	I_E = 10μA, I_C = 0	6.0		V
I_{CEX}	Collector Cutoff Current	V_{CE} = 60V, $V_{EB(off)}$ = 3.0V		10	nA
I_{CBO}	Collector Cutoff Current	V_{CB} = 60V, I_E = 0 V_{CB} = 60V, I_E = 0, T_a = 125°C		0.01 10	μA μA
I_{EBO}	Emitter Cutoff Current	V_{EB} = 3.0V, I_C = 0		10	μA
I_{BL}	Base Cutoff Current	V_{CE} = 60V, $V_{EB(off)}$ = 3.0V		20	μA
On Characteristics					
h_{FE}	DC Current Gain	I_C = 0.1mA, V_{CE} = 10V I_C = 1.0mA, V_{CE} = 10V I_C = 10mA, V_{CE} = 10V I_C = 10mA, V_{CE} = 10V, T_a = -55°C I_C = 150mA, V_{CE} = 10V * I_C = 150mA, V_{CE} = 10V * I_C = 500mA, V_{CE} = 10V *	35 50 75 35 100 50 40	300	
$V_{CE(sat)}$	Collector-Emitter Saturation Voltage *	I_C = 150mA, V_{CE} = 10V I_C = 500mA, V_{CE} = 10V		0.3 1.0	V V
$V_{BE(sat)}$	Base-Emitter Saturation Voltage *	I_C = 150mA, V_{CE} = 10V I_C = 500mA, V_{CE} = 10V	0.6	1.2 2.0	V V

* Pulse Test: Pulse Width ≤ 300μs, Duty Cycle ≤ 2.0%

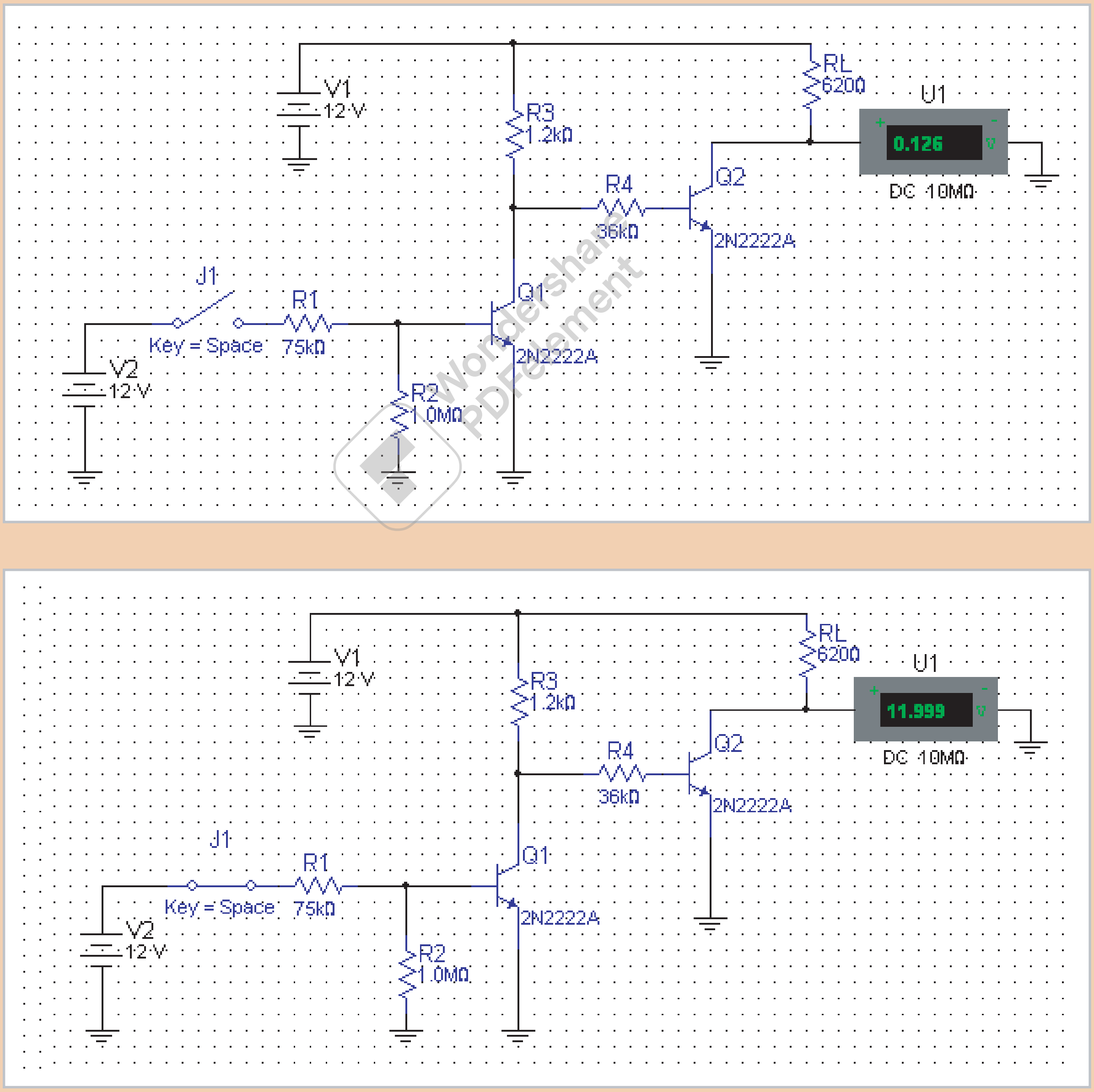
▲ **FIGURE 4–50**

Partial datasheet for the 2N2222A transistor. Copyright Fairchild Semiconductor Corporation. Used by permission.

2. Using the minimum β_{DC} or h_{FE} from the datasheet, determine the base current required to saturate Q_1 at $I_C = 10$ mA.
3. To ensure saturation, calculate the value of R_1 necessary to provide sufficient base current to Q_1 from the +12 V sensor input. R_2 can be any arbitrarily high value to assure the base of Q_1 is near ground when there is no input voltage.
4. Calculate the value of R_4 so that a sufficient base current is supplied to Q_2 to ensure saturation for a load of 620 Ω. This simulates the actual load of the alarm and dialing circuits.

Simulation

The switching circuit is simulated with Multisim, as shown in Figure 4–51. A switch connected to a 12 V source simulates the zone input and a 620 Ω load resistor is connected to



▲ **FIGURE 4–51**

Simulation of the switching circuit.

the output to represent the actual load. When the zone switch is open, Q_2 is saturated as indicated by 0.126 V at its collector. When the zone switch is closed, Q_2 is *off* as indicated by the 11.999 V at its collector.

5. How does the Q_2 saturation voltage compare to the value specified on the datasheet?

Simulate the circuit using your Multisim software. Observe the operation with the virtual multimeter.

Prototyping and Testing

Now that the circuit has been simulated, it is connected on a protoboard and tested for proper operation.

Lab Experiment

To build and test a similar circuit, go to Experiment 4 in your lab manual (*Laboratory Exercises for Electronic Devices* by David Buchla and Steven Wetterling).

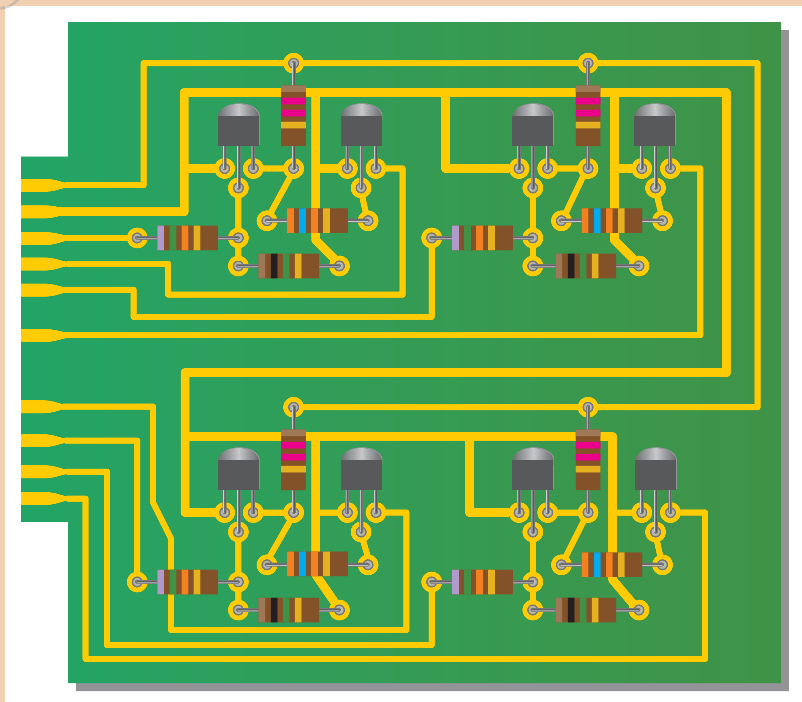
Printed Circuit Board

The transistor switching circuit prototype has been built and tested. It is now committed to a printed circuit layout, as shown in Figure 4–52. Notice that there are four identical circuits on the board, one for each zone to be monitored. The outputs are externally connected to form a single input.

6. Compare the printed circuit board to the schematic in Figure 4–49 and verify that they agree. Identify each component.
7. Compare the resistor values on the printed circuit board to those that you calculated previously. They should closely agree.
8. Label the input and output pins on the printed circuit board according to their function.
9. Describe how you would test the circuit board.
10. Explain how the system can be expanded to monitor six zones instead of four.

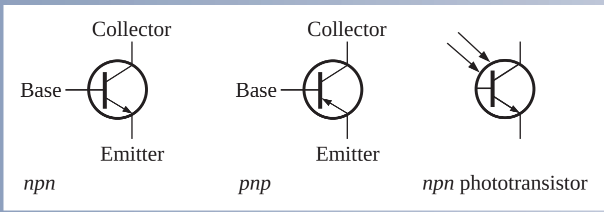
▶ FIGURE 4–52

The 4-zone transistor switching circuit board.

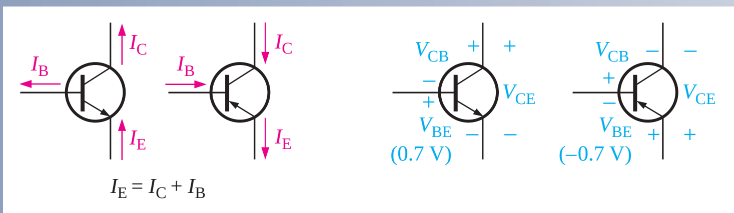


SUMMARY OF BIPOLAR JUNCTION TRANSISTORS

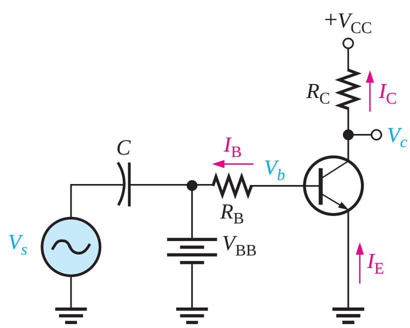
SYMBOLS



CURRENTS AND VOLTAGES



AMPLIFICATION



- DC current gain

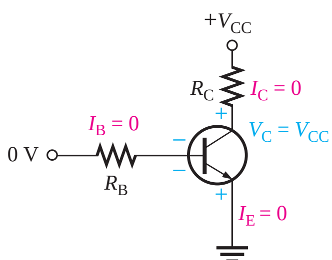
$$I_C = \beta_{DC} I_B$$

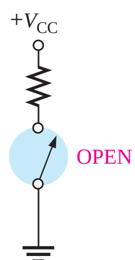
- AC voltage gain

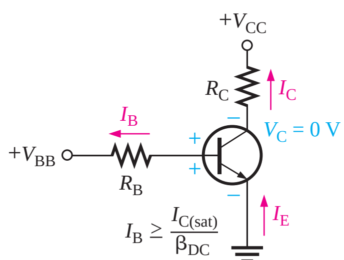
$$A_v = \frac{V_c}{V_b} = \frac{R_C}{r'_e}$$

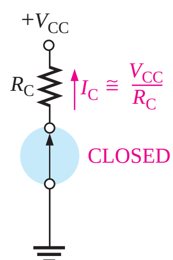
BE junction forward-biased
BC junction reverse-biased

SWITCHING









Cutoff: BE junction reverse-biased
BC junction reverse-biased

Ideal switch equivalent for cutoff

Saturation: BE junction forward-biased
BC junction forward-biased

Ideal switch equivalent for saturation

SUMMARY

Section 4–1
- The BJT (bipolar junction transistor) is constructed with three regions: base, collector, and emitter.
- The BJT has two *pn* junctions, the base-emitter junction and the base-collector junction.
- Current in a BJT consists of both free electrons and holes, thus the term *bipolar*.
- The base region is very thin and lightly doped compared to the collector and emitter regions.
- The two types of bipolar junction transistor are the *npn* and the *pnp*.

Section 4–2
- To operate as an amplifier, the base-emitter junction must be forward-biased and the base-collector junction must be reverse-biased. This is called *forward-reverse bias*.
- The three currents in the transistor are the base current (I_B), emitter current (I_E), and collector current (I_C).
- I_B is very small compared to I_C and I_E.

Section 4–3
- The dc current gain of a transistor is the ratio of I_C to I_B and is designated β_{DC}. Values typically range from less than 20 to several hundred.
- β_{DC} is usually referred to as h_{FE} on transistor datasheets.
- The ratio of I_C to I_E is called α_{DC}. Values typically range from 0.95 to 0.99.
- There is a variation in β_{DC} over temperature and also from one transistor to another of the same type.

Section 4–4
- When a transistor is forward-reverse biased, the voltage gain depends on the internal emitter resistance and the external collector resistance.
- Voltage gain is the ratio of output voltage to input voltage.
- Internal transistor resistances are represented by a lowercase *r*.

Section 4–5
- A transistor can be operated as an electronic switch in cutoff and saturation.
- In cutoff, both *pn* junctions are reverse-biased and there is essentially no collector current. The transistor ideally behaves like an open switch between collector and emitter.
- In saturation, both *pn* junctions are forward-biased and the collector current is maximum. The transistor ideally behaves like a closed switch between collector and emitter.

Section 4–6
- In a phototransistor, base current is produced by incident light.
- A phototransistor can be either a two-lead or a three-lead device.
- An optocoupler consists of an LED and a photodiode or phototransistor.
- Optocouplers are used to electrically isolate circuits.

Section 4–7
- There are many types of transistor packages using plastic, metal, or ceramic.
- Two basic package types are through-hole and surface mount.

Section 4–8
- It is best to check a transistor in-circuit before removing it.
- Common faults in transistor circuits are open junctions, low β_{DC}, excessive leakage currents, and external opens and shorts on the circuit board.

KEY TERMS

Key terms and other bold terms in the chapter are defined in the end-of-book glossary.

Amplification The process of increasing the power, voltage, or current by electronic means.

Base One of the semiconductor regions in a BJT. The base is very thin and lightly doped compared to the other regions.

Beta (β) The ratio of dc collector current to dc base current in a BJT; current gain from base to collector.

BJT A bipolar junction transistor constructed with three doped semiconductor regions separated by two *pn* junctions.

Collector The largest of the three semiconductor regions of a BJT.

Cutoff The nonconducting state of a transistor.

Emitter The most heavily doped of the three semiconductor regions of a BJT.

Gain The amount by which an electrical signal is increased or amplified.

Linear Characterized by a straight-line relationship of the transistor currents.

Phototransistor A transistor in which base current is produced when light strikes the photosensitive semiconductor base region.

Saturation The state of a BJT in which the collector current has reached a maximum and is independent of the base current.

KEY FORMULAS

4–1	$I_E = I_C + I_B$	Transistor currents
4–2	$\beta_{DC} = \dfrac{I_C}{I_B}$	DC current gain
4–3	$V_{BE} \cong 0.7\text{ V}$	Base-to-emitter voltage (silicon)
4–4	$I_B = \dfrac{V_{BB} - V_{BE}}{R_B}$	Base current
4–5	$V_{CE} = V_{CC} - I_C R_C$	Collector-to-emitter voltage (common-emitter)
4–6	$V_{CB} = V_{CE} - V_{BE}$	Collector-to-base voltage
4–7	$A_v \cong \dfrac{R_C}{r'_e}$	Approximate ac voltage gain
4–8	$V_{CE(cutoff)} = V_{CC}$	Cutoff condition
4–9	$I_{C(sat)} = \dfrac{V_{CC} - V_{CE(sat)}}{R_C}$	Collector saturation current
4–10	$I_{B(min)} = \dfrac{I_{C(sat)}}{\beta_{DC}}$	Minimum base current for saturation
4–11	$I_C = \beta_{DC} I_\lambda$	Phototransistor collector current

TRUE/FALSE QUIZ

Answers can be found at www.pearsonhighered.com/floyd.

1. A bipolar junction transistor has three terminals.
2. The three regions of a BJT are base, emitter, and cathode.
3. For operation in the linear or active region, the base-emitter junction of a transistor is forward-biased.
4. Two types of BJT are *npn* and *pnp*.
5. The base current and collector current are approximately equal.
6. The dc voltage gain of a transistor is designated β_{DC}.
7. Cutoff and saturation are the two normal states of a linear transistor amplifier.
8. When a transistor is saturated, the collector current is maximum.
9. β_{DC} and h_{FE} are two different transistor parameters.
10. Voltage gain of a transistor amplifier depends on the collector resistor and the internal ac resistance.
11. Amplification is the output voltage divided by the input current.
12. A transistor in cutoff acts as an open switch.

CIRCUIT-ACTION QUIZ

Answers can be found at www.pearsonhighered.com/floyd.

1. If a transistor with a higher β_{DC} is used in Figure 4–9, the collector current will
   (a) increase **(b)** decrease **(c)** not change
2. If a transistor with a higher β_{DC} is used in Figure 4–9, the emitter current will
   (a) increase **(b)** decrease **(c)** not change

3. If a transistor with a higher β_{DC} is used in Figure 4–9, the base current will
   (a) increase **(b)** decrease **(c)** not change
4. If V_{BB} is reduced in Figure 4–16, the collector current will
   (a) increase **(b)** decrease **(c)** not change
5. If V_{CC} in Figure 4–16 is increased, the base current will
   (a) increase **(b)** decrease **(c)** not change
6. If the amplitude of V_{in} in Figure 4–22 is decreased, the ac output voltage amplitude will
   (a) increase **(b)** decrease **(c)** not change
7. If the transistor in Figure 4–24 is saturated and the base current is increased, the collector current will
   (a) increase **(b)** decrease **(c)** not change
8. If R_C in Figure 4–24 is reduced in value, the value of $I_{C(sat)}$ will
   (a) increase **(b)** decrease **(c)** not change
9. If the transistor in Figure 4–38 is open from collector to emitter, the voltage across R_C will
   (a) increase **(b)** decrease **(c)** not change
10. If the transistor in Figure 4–38 is open from collector to emitter, the collector voltage will
    (a) increase **(b)** decrease **(c)** not change
11. If the base resistor in Figure 4–38 is open, the transistor collector voltage will
    (a) increase **(b)** decrease **(c)** not change
12. If the emitter in Figure 4–38 becomes disconnected from ground, the collector voltage will
    (a) increase **(b)** decrease **(c)** not change

SELF-TEST

Answers can be found at www.pearsonhighered.com/floyd.

Section 4–1

1. The three terminals of a bipolar junction transistor are called
   (a) *p*, *n*, *p* **(b)** *n*, *p*, *n* **(c)** input, output, ground **(d)** base, emitter, collector
2. In a *pnp* transistor, the *p* regions are
   (a) base and emitter **(b)** base and collector **(c)** emitter and collector

Section 4–2

3. For operation as an amplifier, the base of an *npn* transistor must be
   (a) positive with respect to the emitter **(b)** negative with respect to the emitter
   (c) positive with respect to the collector **(d)** 0 V
4. The emitter current is always
   (a) greater than the base current **(b)** less than the collector current
   (c) greater than the collector current **(d)** answers (a) and (c)

Section 4–3

5. The β_{DC} of a transistor is its
   (a) current gain **(b)** voltage gain **(c)** power gain **(d)** internal resistance
6. If I_C is 50 times larger than I_B, then β_{DC} is
   (a) 0.02 **(b)** 100 **(c)** 50 **(d)** 500
7. The approximate voltage across the forward-biased base-emitter junction of a silicon BJT is
   (a) 0 V **(b)** 0.7 V **(c)** 0.3 V **(d)** V_{BB}
8. The bias condition for a transistor to be used as a linear amplifier is called
   (a) forward-reverse **(b)** forward-forward **(c)** reverse-reverse **(d)** collector bias

Section 4–4

9. If the output of a transistor amplifier is 5 V rms and the input is 100 mV rms, the voltage gain is
   (a) 5 **(b)** 500 **(c)** 50 **(d)** 100
10. When a lowercase r' is used in relation to a transistor, it refers to
    (a) a low resistance **(b)** a wire resistance
    (c) an internal ac resistance **(d)** a source resistance

11. In a given transistor amplifier, $R_C = 2.2\ \text{k}\Omega$ and $r'_e = 20\ \Omega$, the voltage gain is
    (a) 2.2 **(b)** 110 **(c)** 20 **(d)** 44

Section 4–5

12. When operated in cutoff and saturation, the transistor acts like a
    (a) linear amplifier **(b)** switch **(c)** variable capacitor **(d)** variable resistor
13. In cutoff, V_{CE} is
    (a) 0 V **(b)** minimum **(c)** maximum
    (d) equal to V_{CC} **(e)** answers (a) and (b) **(f)** answers (c) and (d)
14. In saturation, V_{CE} is
    (a) 0.7 V **(b)** equal to V_{CC} **(c)** minimum **(d)** maximum
15. To saturate a BJT,
    (a) $I_B = I_{C(sat)}$ **(b)** $I_B > I_{C(sat)}/\beta_{DC}$
    (c) V_{CC} must be at least 10 V **(d)** the emitter must be grounded
16. Once in saturation, a further increase in base current will
    (a) cause the collector current to increase **(b)** not affect the collector current
    (c) cause the collector current to decrease **(d)** turn the transistor off

Section 4–6

17. In a phototransistor, base current is
    (a) set by a bias voltage **(b)** directly proportional to light intensity
    (c) inversely proportional to light intensity **(d)** not a factor
18. The relationship between the collector current and a light-generated base current is
    (a) $I_C = \beta_{DC}I_\lambda$ **(b)** $I_C = \alpha_{DC}I_\lambda$ **(c)** $I_C = \lambda I_\lambda$ **(d)** $I_C = \beta^2_{DC}I_\lambda$
19. An optocoupler usually consists of
    (a) two LEDs **(b)** an LED and a photodiode
    (c) an LED and a phototransistor **(d)** both (b) and (c)

Section 4–8

20. In a transistor amplifier, if the base-emitter junction is open, the collector voltage is
    (a) V_{CC} **(b)** 0 V **(c)** floating **(d)** 0.2 V
21. A DMM measuring on open transistor junction shows
    (a) 0 V **(b)** 0.7 V **(c)** OL **(d)** V_{CC}

PROBLEMS

Answers to all odd-numbered problems are at the end of the book.

BASIC PROBLEMS

Section 4–1 **Bipolar Junction Transistor (BJT) Structure**

1. What are the majority carriers in the base region of an *npn* transistor called?
2. Explain the purpose of a thin, lightly doped base region.

Section 4–2 **Basic BJT Operation**

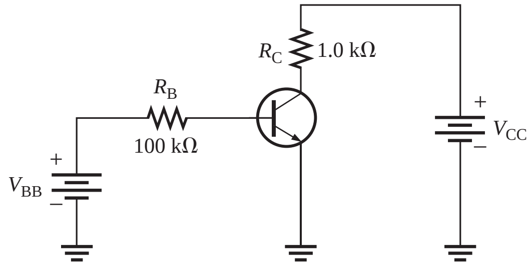
3. Why is the base current in a transistor so much less than the collector current?
4. In a certain transistor circuit, the base current is 2 percent of the 30 mA emitter current. Determine the collector current.
5. For normal operation of a *pnp* transistor, the base must be (+ or −) with respect to the emitter, and (+ or −) with respect to the collector.
6. What is the value of I_C for $I_E = 5.34$ mA and $I_B = 475\ \mu$A?

Section 4–3 **BJT Characteristics and Parameters**

7. What is the α_{DC} when $I_C = 8.23$ mA and $I_E = 8.69$ mA?
8. A certain transistor has an $I_C = 25$ mA and an $I_B = 200\ \mu$A. Determine the β_{DC}.
9. What is the β_{DC} of a transistor if $I_C = 20.3$ mA and $I_E = 20.5$ mA?
10. What is the α_{DC} if $I_C = 5.35$ mA and $I_B = 50\ \mu$A?
11. A certain transistor exhibits an α_{DC} of 0.96. Determine I_C when $I_E = 9.35$ mA.

12. A base current of 50 μA is applied to the transistor in Figure 4–53, and a voltage of 5 V is dropped across R_C. Determine the β_{DC} of the transistor.

▶ **FIGURE 4–53**



13. Calculate α_{DC} for the transistor in Problem 12.

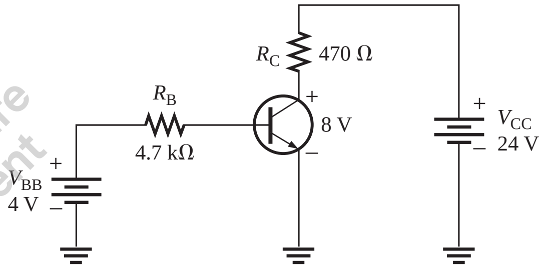
14. Assume that the transistor in the circuit of Figure 4–53 is replaced with one having a β_{dc} of 200. Determine I_B, I_C, I_E, and V_{CE} given that $V_{CC} = 10$ V and $V_{BB} = 3$ V.

15. If V_{CC} is increased to 15 V in Figure 4–53, how much do the currents and V_{CE} change?

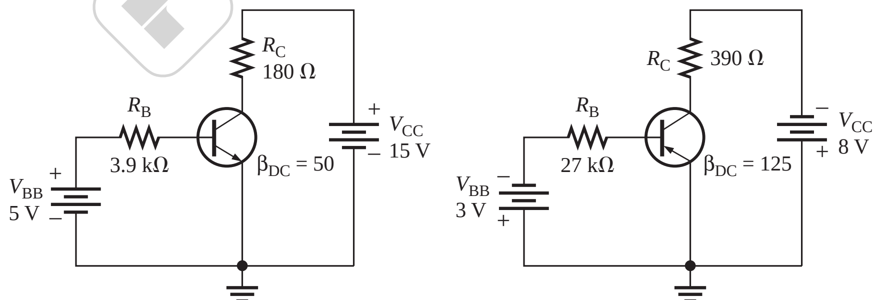
16. Determine each current in Figure 4–54. What is the β_{DC}?

▶ **FIGURE 4–54**

Multisim file circuits are identified with a logo and are in the Problems folder on the companion website. Filenames correspond to figure numbers (e.g., F04-54).



17. Find V_{CE}, V_{BE}, and V_{CB} in both circuits of Figure 4–55.



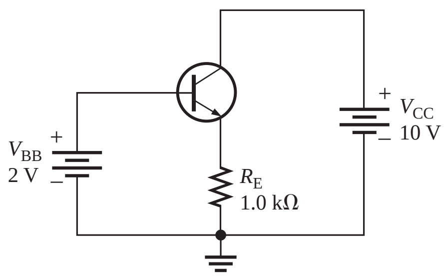
(a) (b)

▲ **FIGURE 4–55**

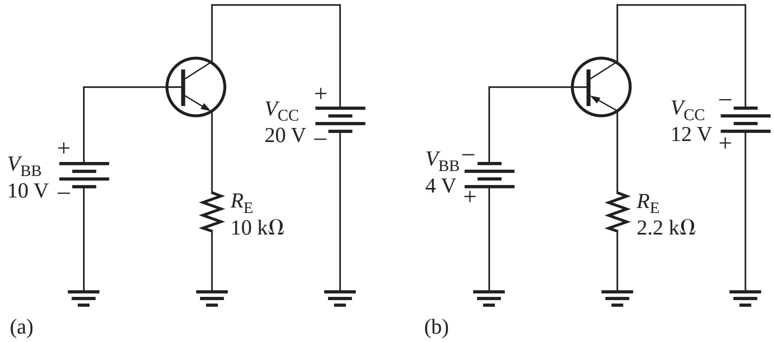
18. Determine whether or not the transistors in Figure 4–55 are saturated.

19. Find I_B, I_E, and I_C in Figure 4–56. $\alpha_{DC} = 0.98$.

▶ **FIGURE 4–56**



20. Determine the terminal voltages of each transistor with respect to ground for each circuit in Figure 4–57. Also determine V_{CE}, V_{BE}, and V_{CB}.



▲ FIGURE 4–57

21. If the β_{DC} in Figure 4–57(a) changes from 100 to 150 due to a temperature increase, what is the change in collector current?

22. A certain transistor is to be operated at a collector current of 50 mA. How high can V_{CE} go without exceeding a $P_{D(max)}$ of 1.2 W?

23. The power dissipation derating factor for a certain transistor is 1 mW/°C. The $P_{D(max)}$ is 0.5 W at 25°C. What is $P_{D(max)}$ at 100°C?

Section 4–4 The BJT as an Amplifier

24. A transistor amplifier has a voltage gain of 50. What is the output voltage when the input voltage is 100 mV?

25. To achieve an output of 10 V with an input of 300 mV, what voltage gain is required?

26. A 50 mV signal is applied to the base of a properly biased transistor with $r'_e = 10\ \Omega$ and $R_C = 560\ \Omega$. Determine the signal voltage at the collector.

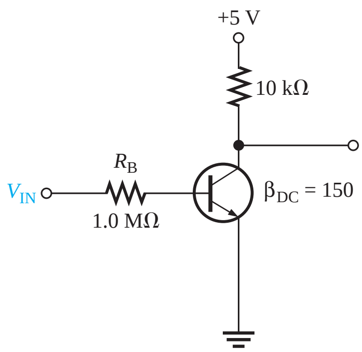
27. Determine the value of the collector resistor in an *npn* transistor amplifier with $\beta_{DC} = 250$, $V_{BB} = 2.5$ V, $V_{CC} = 9$ V, $V_{CE} = 4$ V, and $R_B = 100$ kΩ.

28. What is the dc current gain of each circuit in Figure 4–55?

Section 4–5 The BJT as a Switch

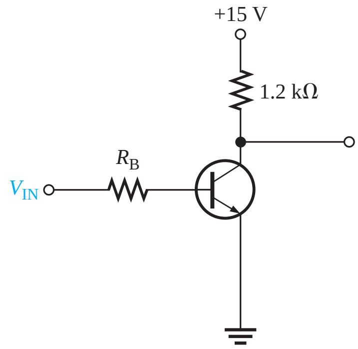
29. Determine $I_{C(sat)}$ for the transistor in Figure 4–58. What is the value of I_B necessary to produce saturation? What minimum value of V_{IN} is necessary for saturation? Assume $V_{CE(sat)} = 0$ V.

► FIGURE 4–58



30. The transistor in Figure 4–59 has a β_{DC} of 50. Determine the value of R_B required to ensure saturation when V_{IN} is 5 V. What must V_{IN} be to cut off the transistor? Assume $V_{CE(sat)} = 0$ V.

▶ FIGURE 4–59

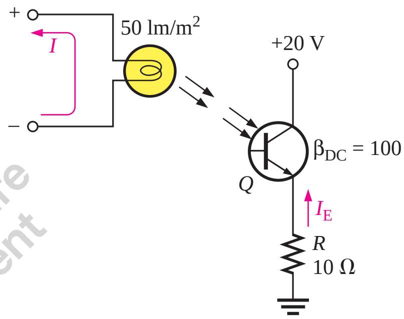


Section 4–6 The Phototransistor

31. A certain phototransistor in a circuit has a $\beta_{DC} = 200$. If $I_\lambda = 100\ \mu A$, what is the collector current?

32. Determine the emitter current in the phototransistor circuit in Figure 4–60 if, for each lm/m^2 of light intensity, 1 μA of base current is produced in the phototransistor.

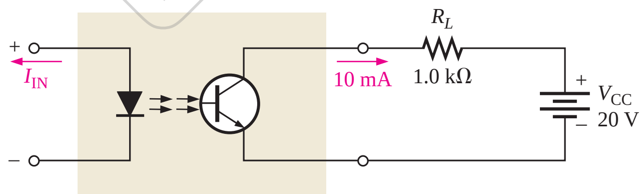
▶ FIGURE 4–60



33. A particular optical coupler has a current transfer ratio of 30 percent. If the input current is 100 mA, what is the output current?

34. The optical coupler shown in Figure 4–61 is required to deliver at least 10 mA to the external load. If the current transfer ratio is 60 percent, how much current must be supplied to the input?

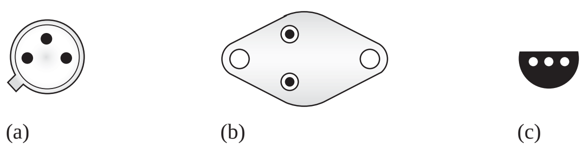
▶ FIGURE 4–61



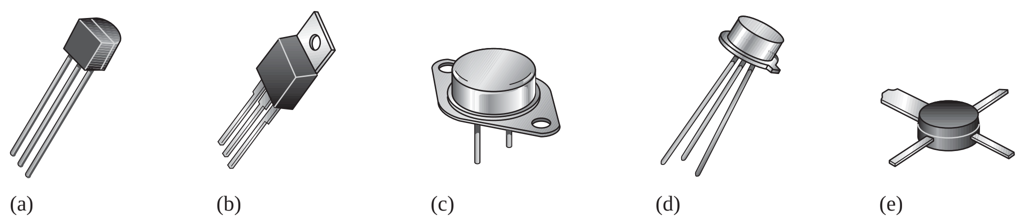
Section 4–7 Transistor Categories and Packaging

35. Identify the leads on the transistors in Figure 4–62. Bottom views are shown.

▶ FIGURE 4–62



36. What is the most probable category of each transistor in Figure 4–63?

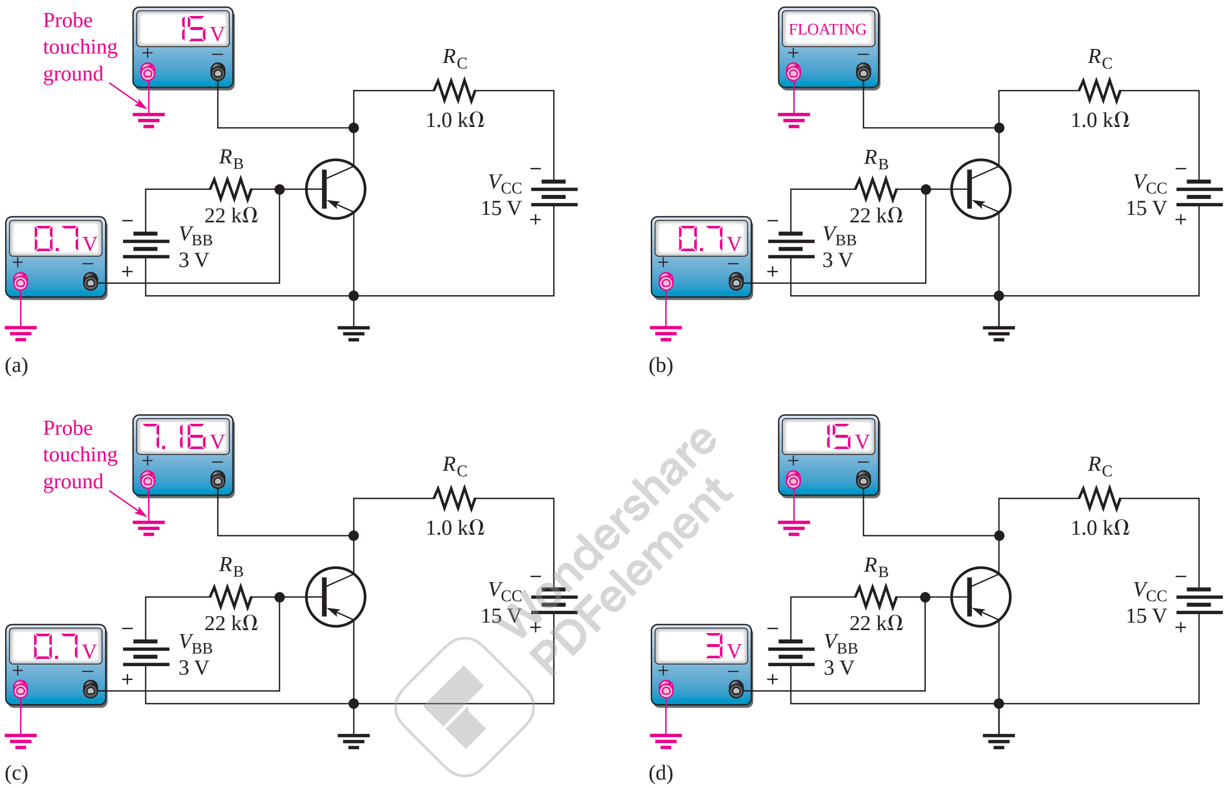


▲ FIGURE 4–63

Section 4–8 Troubleshooting

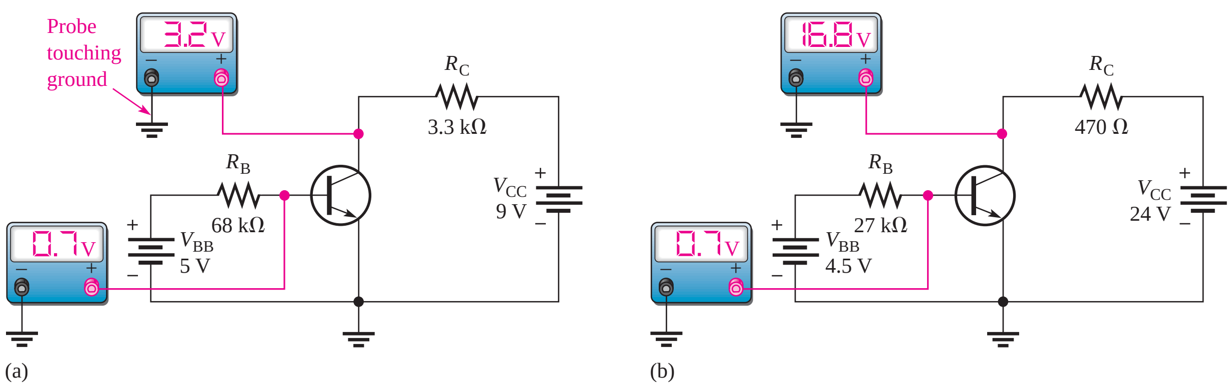
37. In an out-of-circuit test of a good *npn* transistor, what should an analog ohmmeter indicate when its positive probe is touching the emitter and the negative probe is touching the base? When its positive probe is touching the base and the negative probe is touching the collector?

38. What is the most likely problem, if any, in each circuit of Figure 4–64? Assume a β_{DC} of 75.



▲ FIGURE 4–64

39. What is the value of the β_{DC} of each transistor in Figure 4–65?



▲ FIGURE 4–65

APPLICATION ACTIVITY PROBLEMS

40. Calculate the power dissipation in each resistor in Figure 4–51 for both states of the circuit.

41. Determine the minimum value of load resistance that Q_2 can drive without exceeding the maximum collector current specified on the datasheet.

42. Develop a wiring diagram for the printed circuit board in Figure 4–52 for connecting it in the security alarm system. The input/output pins are numbered from 1 to 10 starting at the top.

DATASHEET PROBLEMS

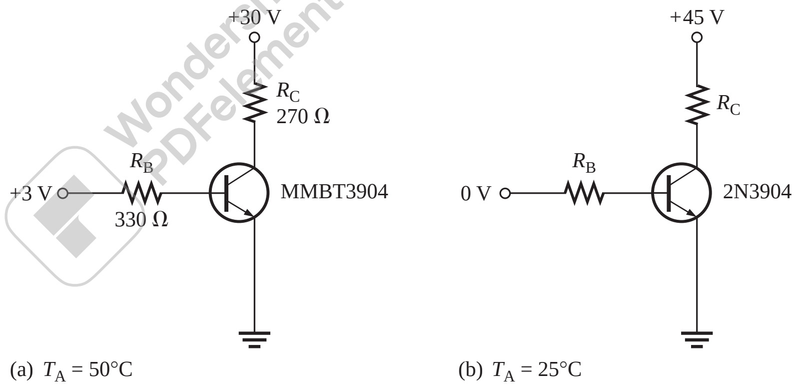
43. Refer to the partial transistor datasheet in Figure 4–20.

- **(a)** What is the maximum collector-to-emitter voltage for a 2N3904?
- **(b)** How much continuous collector current can the 2N3904 handle?
- **(c)** How much power can a 2N3904 dissipate if the ambient temperature is 25°C?
- **(d)** How much power can a 2N3904 dissipate if the ambient temperature is 50°C?
- **(e)** What is the minimum h_{FE} of a 2N3904 if the collector current is 1 mA?

44. Refer to the transistor datasheet in Figure 4–20. A MMBT3904 is operating in an environment where the ambient temperature is 65°C. What is the most power that it can dissipate?

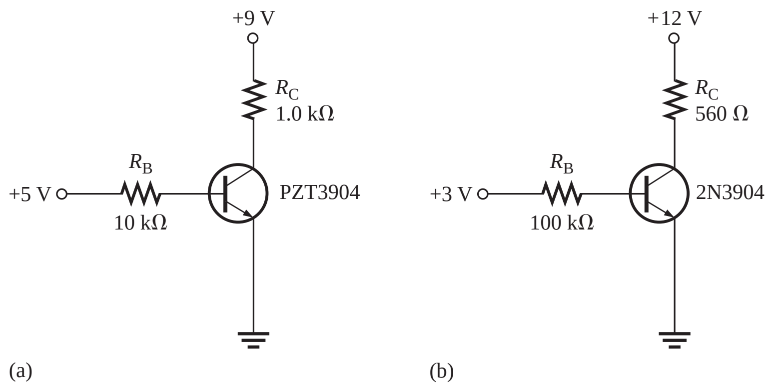
45. Refer to the transistor datasheet in Figure 4–20. A PZT3904 is operating with an ambient temperature of 45°C. What is the most power that it can dissipate?

46. Refer to the transistor datasheet in Figure 4–20. Determine if any rating is exceeded in each circuit of Figure 4–66 based on minimum specified values.



▲ FIGURE 4–66

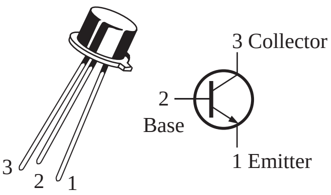
47. Refer to the transistor datasheet in Figure 4–20. Determine whether or not the transistor is saturated in each circuit of Figure 4–67 based on the maximum specified value of h_{FE}.



▲ FIGURE 4–67

48. Refer to the partial transistor datasheet in Figure 4–68. Determine the minimum and maximum base currents required to produce a collector current of 10 mA in a 2N3946. Assume that the transistor is not in saturation and $V_{CE} = 1$ V.

2N3946
2N3947



General-Purpose Transistors

NPN Silicon

Maximum Ratings

Rating	Symbol	Value	Unit
Collector-Emitter voltage	V_{CEO}	40	V dc
Collector-Base voltage	V_{CBO}	60	V dc
Emitter-Base voltage	V_{EBO}	6.0	V dc
Collector current — continuous	I_C	200	mA dc
Total device dissipation @ T_A = 25°C Derate above 25°C	P_D	0.36 2.06	Watts mW/°C
Total device dissipation @ T_C = 25°C Derate above 25°C	P_D	1.2 6.9	Watts mW/°C
Operating and storage junction Temperature range	T_J, T_{stg}	–65 to +200	°C

Thermal Characteristics

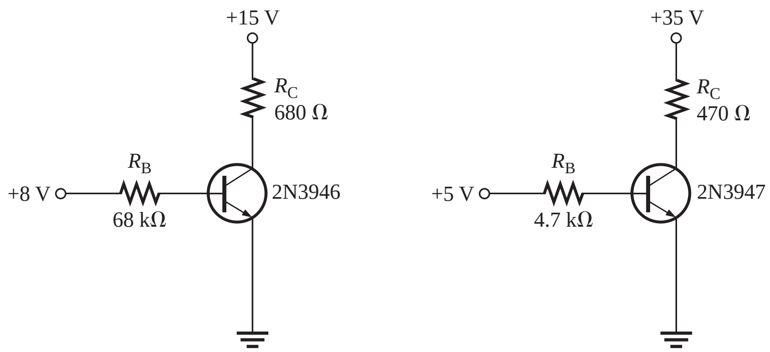
Characteristic	Symbol	Max	Unit
Thermal resistance, junction to case	$R_{\theta JC}$	0.15	°C/mW
Thermal resistance, junction to ambient	$R_{\theta JA}$	0.49	°C/mW

Electrical Characteristics (T_A = 25°C unless otherwise noted.)

Characteristic		Symbol	Min	Max	Unit
OFF Characteristics					
Collector-Emitter breakdown voltage (I_C = 10 mA dc)		$V_{(BR)CEO}$	40	–	V dc
Collector-Base breakdown voltage (I_C = 10 μA dc, I_E = 0)		$V_{(BR)CBO}$	60	–	V dc
Emitter-Base breakdown voltage (I_E = 10 μA dc, I_C = 0)		$V_{(BR)EBO}$	6.0	–	V dc
Collector cutoff current (V_{CE} = 40 V dc, V_{OB} = 3.0 V dc) (V_{CE} = 40 V dc, V_{OB} = 3.0 V dc, T_A = 150°C)		I_{CEX}	 – –	 0.010 15	μA dc
Base cutoff current (V_{CE} = 40 V dc, V_{OB} = 3.0 V dc)		I_{BL}	–	.025	μA dc
ON Characteristics					
DC current gain (I_C = 0.1 mA dc, V_{CE} = 1.0 V dc)	 2N3946 2N3947	h_{FE}	 30 60	 – –	–
(I_C = 1.0 mA dc, V_{CE} = 1.0 V dc)	2N3946 2N3947		45 90	– –	
(I_C = 10 mA dc, V_{CE} = 1.0 V dc)	2N3946 2N3947		50 100	150 300	
(I_C = 50 mA dc, V_{CE} = 1.0 V dc)	2N3946 2N3947		20 40	– –	
Collector-Emitter saturation voltage (I_C = 10 mA dc, I_B = 1.0 mA dc) (I_C = 50 mA dc, I_B = 5.0 mA dc)		$V_{CE(sat)}$	 – –	 0.2 0.3	V dc
Base-Emitter saturation voltage (I_C = 10 mA dc, I_B = 1.0 mA dc) (I_C = 50 mA dc, I_B = 5.0 mA dc)		$V_{BE(sat)}$	 0.6 –	 0.9 1.0	V dc
Small-Signal Characteristics					
Current gain — Bandwidth product (I_C = 10 mA dc, V_{CE} = 20 V dc, f = 100 MHz)	 2N3946 2N3947	f_T	 250 300	 – –	MHz
Output capacitance (V_{CB} = 10 V dc, I_E = 0, f = 100 kHz)		C_{obo}	–	4.0	pF

▲ FIGURE 4–68

49. For each of the circuits in Figure 4–69, determine if there is a problem based on the datasheet information in Figure 4–68. Use the maximum specified h_{FE}.



(a) $T_A = 40°C$ (b) $T_A = 25°C$

▲ FIGURE 4–69

ADVANCED PROBLEMS

50. Derive a formula for α_{DC} in terms of β_{DC}.

51. A certain 2N3904 dc bias circuit with the following values is in saturation. $I_B = 500\ \mu A$, $V_{CC} = 10$ V, and $R_C = 180\ \Omega$, $h_{FE} = 150$. If you increase V_{CC} to 15 V, does the transistor come out of saturation? If so, what is the collector-to-emitter voltage and the collector current?

52. Design a dc bias circuit for a 2N3904 operating from a collector supply voltage of 9 V and a base-bias voltage of 3 V that will supply 150 mA to a resistive load that acts as the collector resistor. The circuit must not be in saturation. Assume the minimum specified β_{DC} from the datasheet.

53. Modify the design in Problem 52 to use a single 9 V dc source rather than two different sources. Other requirements remain the same.

54. Design a dc bias circuit for an amplifier in which the voltage gain is to be a minimum of 50 and the output signal voltage is to be “riding” on a dc level of 5 V. The maximum input signal voltage at the base is 10 mV rms. $V_{CC} = 12$ V, and $V_{BB} = 4$ V. Assume $r'_e = 8\ \Omega$.

MULTISIM TROUBLESHOOTING PROBLEMS

These file circuits are in the Troubleshooting Problems folder on the companion website.

55. Open file TSP04-55 and determine the fault.

56. Open file TSP04-56 and determine the fault.

57. Open file TSP04-57 and determine the fault.

58. Open file TSP04-58 and determine the fault.

59. Open file TSP04-59 and determine the fault.

60. Open file TSP04-60 and determine the fault.

61. Open file TSP04-61 and determine the fault.

62. Open file TSP04-62 and determine the fault.

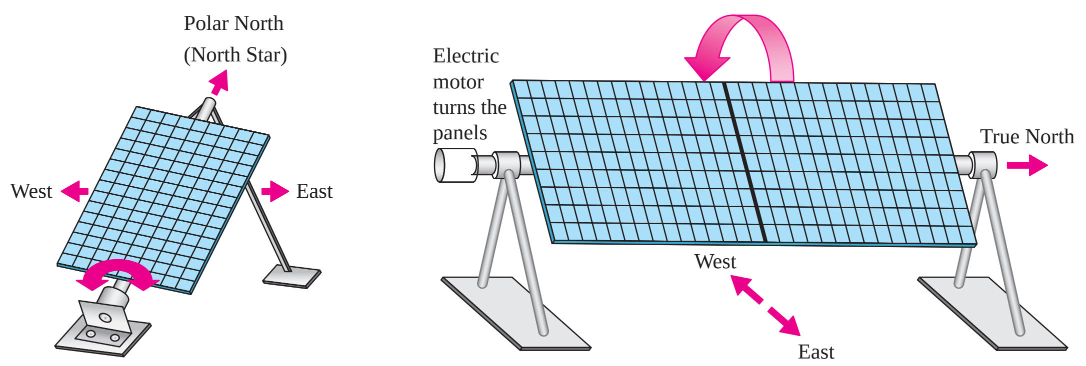
GreenTech Application 4: *Solar Power*

In this GreenTech Application, solar tracking is examined. Solar tracking is the process of moving the solar panel to track the daily movement of the sun and the seasonal changes in elevation of the sun in the southern sky. The purpose of a solar tracker is to increase the amount of solar energy that can be collected by the system. For flat-panel collectors, an increase of 30% to 50% in collected energy can be realized with sun tracking compared to fixed solar panels.

Before looking at methods for tracking, let's review how the sun moves across the sky. The daily motion of the sun follows the arc of a circle from east to west that has its axis pointed north near the location of the North Star. As the seasons change from the winter solstice to the summer solstice, the sun rises a little further to the north each day. Between the summer solstice and the winter solstice, the sun moves further south each day. The amount of the north-south motion depends on your location.

Single-Axis Solar Tracking

For flat-panel solar collectors, the most economical and generally most practical solution to tracking is to follow the daily east-west motion, and not the annual north-south motion. The daily east-to-west motion can be followed with a single-axis tracking system. There are two basic single-axis systems: polar and azimuth. In a polar system, the main axis is pointed to the polar north (North Star), as shown in Figure GA4–1(a). (In telescope terminology, this is called an equatorial mounting.) The advantage is that the solar panel is kept at an angle facing the sun at all times because it tracks the sun from east to west and is angled toward the southern sky. In an azimuth tracking system, the motor drives the solar panel and frequently multiple panels. The panels can be oriented horizontally but still track the east-to-west motion of the sun. Although this does not intercept as much of the sunlight during the seasons, it has less wind loading and is more feasible for long rows of solar panels. Figure GA4–1(b) shows a solar array that is oriented horizontally with the axis pointing to true north and uses azimuth tracking (east to west). As you can see, sunlight will strike the polar-aligned panel more directly during the seasonal movement of the sun than it will with the horizontal orientation of the azimuth tracker.



(a) A single-axis polar-aligned tracker

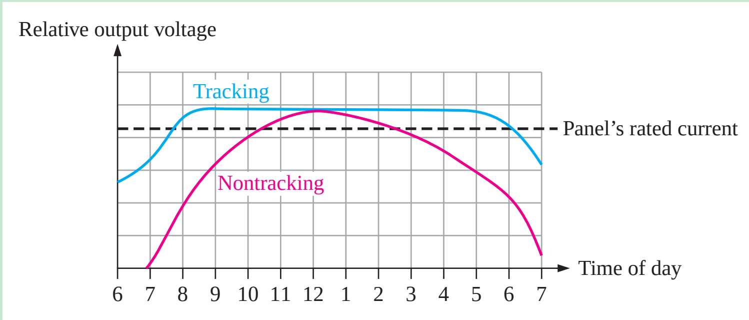
(b) Single-axis azimuth tracker

▲ FIGURE GA4–1

Types of single-axis solar tracking.

Some solar tracking systems combine both the azimuth and the elevation tracking, which is known as dual-axis tracking. Ideally, the solar panel should always face directly toward the sun so that the sun light rays are perpendicular to the panel. With dual-axis tracking, the annual north-south motion of the sun can be followed in addition to the daily east-to-west movement. This is particularly important with concentrating collectors that need to be oriented correctly to focus the sun on the active region.

Figure GA4–2 is an example showing the improvement in energy collection of a typical tracking panel versus a nontracking panel for a flat solar collector. As you can see, tracking extends the time that a given output can be maintained.



▶ **FIGURE GA4–2**

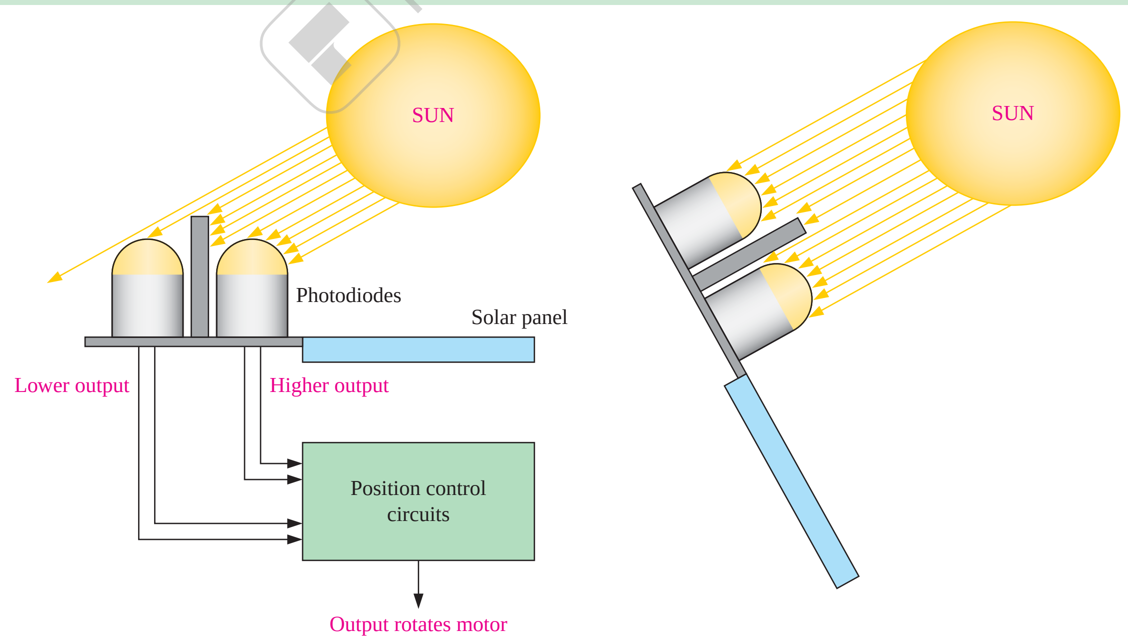
Graphs of voltages in tracking and nontracking (fixed) solar panels.

There are several methods of implementing solar tracking. Two main ones are sensor controlled and timer controlled.

Sensor-Controlled Solar Tracking

This type of tracking control uses photosensitive devices such as photodiodes or photoresistors. Typically, there are two light sensors for the azimuth control and two for the elevation control. Each pair senses the direction of light from the sun and activates the motor control to move the solar panel to align perpendicular to the sun's rays.

Figure GA4–3 shows the basic idea of a sensor-controlled tracker. Two photodiodes with a light-blocking partition between them are mounted on the same plane as the solar panel.



(a) Outputs of the photodiodes are unequal if solar panel is not directly facing the sun.

(b) Outputs of the photodiodes are equal when solar panel orientation is optimum.

▲ **FIGURE GA4–3**

Simplified illustration of a light-sensing control for a solar-tracking system. Relative sizes are exaggerated to demonstrate the concept.

If the solar panel is not facing directly toward the sun, the light strikes the panel and the photodiode assembly at an angle so that one of the diodes is shaded or partially shaded by the partition and receives less light than the other, as illustrated in Figure GA4–3(a). As a result, the photodiode with the most light produces a higher current than the partially-shaded device. The difference in currents from the two diodes is sensed by an operational amplifier and sends an output voltage to the motor. The motor rotates the solar panel until both photodiodes produce the same current and then is stopped by the control circuit, as illustrated in Figure GA4–3(b). The light-blocking partition between the diodes is oriented vertically for azimuth tracking and horizontally for elevation tracking. The photodiode assemblies must face in the same direction as the solar panel, so they are mounted on the solar panel frame.

Dual-Axis Solar Tracking As mentioned, a dual-axis system tracks the sun in both azimuth and elevation. It requires two photo-sensing elements and two motors, as shown in Figure GA4–4. The outputs from the two pairs of sensors go to the position-control circuits. A circuit detects the differential between the two azimuth sensor outputs and, if the differential is sufficient, the azimuth motor is advanced westward until a balance occurs between the two sensors. Similarly, another circuit detects the differential between the two elevation sensor outputs and, correspondingly, advances the elevation motor to rotate the solar panel either up or down until a balance occurs between the two sensors. When night falls and the solar panel is at its western-most position, the position-control circuits detect no output from the azimuth sensors and send a reset command to the azimuth motor to cause it to turn the soar panel back to its eastmost position to await sunrise the next day. The system must be sensitive enough to detect very small differences in photodiode output because the more closely the sun is tracked, the better the energy collection efficiency.

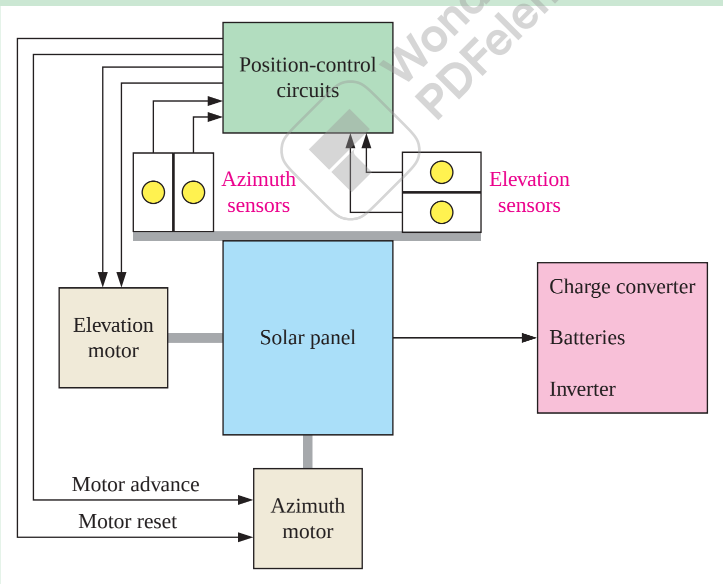


FIGURE GA4–4
Block diagram of a dual-axis sensor-controlled tracking solar power system.

A drawback of the sensor-controlled system is its sensitivity requirement for cloudy days or a passing cloud, when the differences in detected light are much smaller. The system must be able to distinguish between two low-light levels. Also, a certain amount of energy must be diverted to power the electronics and motors, although this is a requirement of most types of tracking systems.

Timer-Controlled Solar Tracking

Solar tracking can also be accomplished by using an electronic timer that causes the motors to move incrementally in azimuth and elevation. During the day the sun moves from east-to-west and this takes approximately 12 hours at summer solstice. The sun moves at a rate of approximately 15° per hour. A timer-controlled tracking system can be designed to follow the sun at desired increments. For example, the panel azimuth position could advance every minute (60 times an hour), every 5 minutes (12 times an hour), or every 15 minutes (4 times an hour), depending on the tracking accuracy desired.

The sun moves slowly in elevation as it progresses from winter solstice to summer solstice and back again, traversing an angle of 47° in six months. This is a rate of 8° per month. The tracking system could make one adjustment in the elevation or tilt of the solar panel each week or each month, depending on the accuracy desired.

Generally, a timer-controlled tracker uses an accurate time source, such as a crystal oscillator, a microprocessor with associated timing and control circuits, and motor interface circuits. The advantage of this type of tracking is that it is independent of the amount of sunlight that is striking the solar panel. Like the sensor-controlled system, the electronics and motors use extra energy. A simple block diagram is shown in Figure GA4–5.

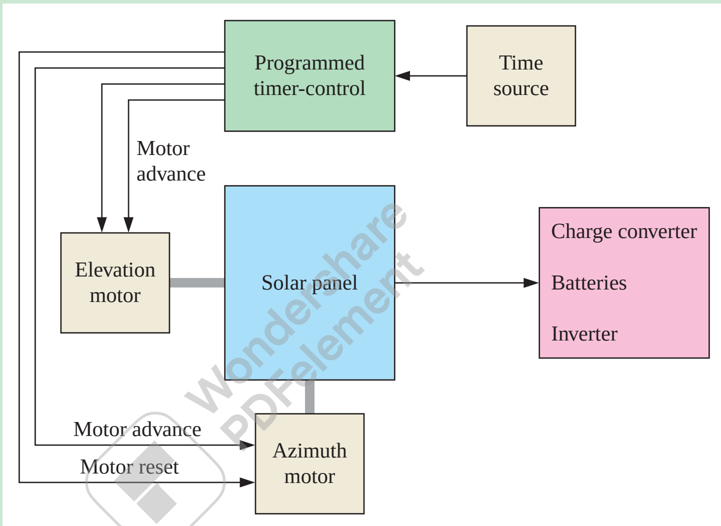


FIGURE GA4–5

Block diagram of a dual-axis timer-controlled tracking solar power system.

Questions

Some questions may require research beyond the content of this coverage. Answers can be found at www.pearsonhighered.com/floyd.

1. What are two types of solar trackers in terms of the way they move?
2. What is the difference between azimuth and elevation?
3. On what date does the winter solstice occur?
4. On what date does the summer solstice occur?
5. Would you recommend a single-axis or a dual-axis tracker for a flat-panel collector? Why?

The following recommended websites are for viewing solar tracking in action. Many other websites are also available.

http://www.youtube.com/watch?v=L4zwQbWrW-A

http://www.youtube.com/watch?v=jdPTyPIwap0

http://www.youtube.com/watch?v=jG942sw31mI

http://www.youtube.com/watch?v=Uzm5LWeTomY

http://www.youtube.com/watch?v=HrnlfiG6KTI

http://www.youtube.com/watch?v=sRqmTpozPYA

http://www.youtube.com/watch?v=E9r1UScgGnE

5 Transistor Bias Circuits

Chapter Outline

5–1 The DC Operating Point
5–2 Voltage-Divider Bias
5–3 Other Bias Methods
5–4 Troubleshooting
Application Activity
GreenTech Application 5: *Wind Power*

Chapter Objectives

- Discuss and determine the dc operating point of a linear amplifier
- Analyze a voltage-divider biased circuit
- Analyze an emitter bias circuit, a base bias circuit, an emitter-feedback bias circuit, and a collector-feedback bias circuit
- Troubleshoot faults in transistor bias circuits

Key Terms

- Q-point
- DC load line
- Linear region
- Stiff voltage divider
- Feedback

Visit the Companion Website

Study aids and Multisim files for this chapter are available at http://www.pearsonhighered.com/electronics

Introduction

As you learned in Chapter 4, a transistor must be properly biased in order to operate as an amplifier. DC biasing is used to establish fixed dc values for the transistor currents and voltages called the *dc operating point* or *quiescent point* (*Q-point*). In this chapter, several types of bias circuits are discussed. This material lays the groundwork for the study of amplifiers, and other circuits that require proper biasing.

Application Activity Preview

The Application Activity focuses on a system for controlling temperature in an industrial chemical process. You will be dealing with a circuit that converts a temperature measurement to a proportional voltage that is used to adjust the temperature of a liquid in a storage tank. The first step is to learn all you can about transistor operation. You will then apply your knowledge to the Application Activity at the end of the chapter.

5–1 THE DC OPERATING POINT

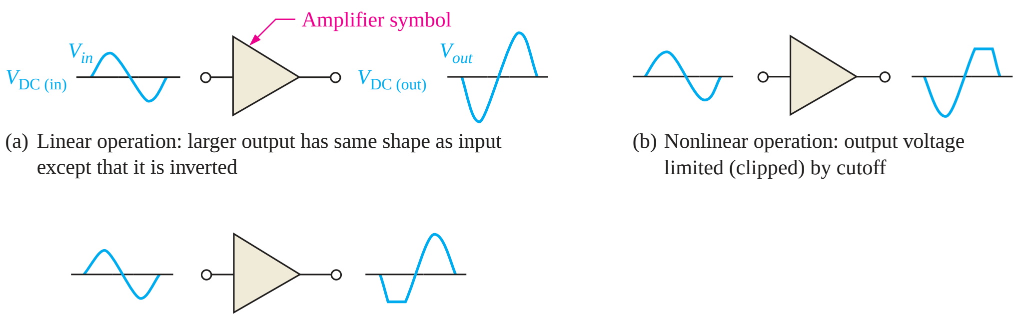
A transistor must be properly biased with a dc voltage in order to operate as a linear amplifier. A dc operating point must be set so that signal variations at the input terminal are amplified and accurately reproduced at the output terminal. As you learned in Chapter 4, when you bias a transistor, you establish the dc voltage and current values. This means, for example, that at the dc operating point, I_C and V_{CE} have specified values. The dc operating point is often referred to as the Q-point (quiescent point).

After completing this section, you should be able to

- **Discuss and determine the dc operating point of a linear amplifier**
- Explain the purpose of dc bias
  - ◆ Define *Q-point* and describe how it affects the output of an amplifier
  - ◆ Explain how collector characteristic curves are produced ◆ Describe and draw a dc load line ◆ State the conditions for linear operation ◆ Explain what causes waveform distortion

DC Bias

Bias establishes the dc operating point (**Q-point**) for proper linear operation of an amplifier. If an amplifier is not biased with correct dc voltages on the input and output, it can go into saturation or cutoff when an input signal is applied. Figure 5–1 shows the effects of proper and improper dc biasing of an inverting amplifier. In part (a), the output signal is an amplified replica of the input signal except that it is inverted, which means that it is 180° out of phase with the input. The output signal swings equally above and below the dc bias level of the output, $V_{DC(out)}$. Improper biasing can cause distortion in the output signal, as illustrated in parts (b) and (c). Part (b) illustrates limiting of the positive portion of the output voltage as a result of a Q-point (dc operating point) being too close to cutoff. Part (c) shows limiting of the negative portion of the output voltage as a result of a dc operating point being too close to saturation.



(a) Linear operation: larger output has same shape as input except that it is inverted

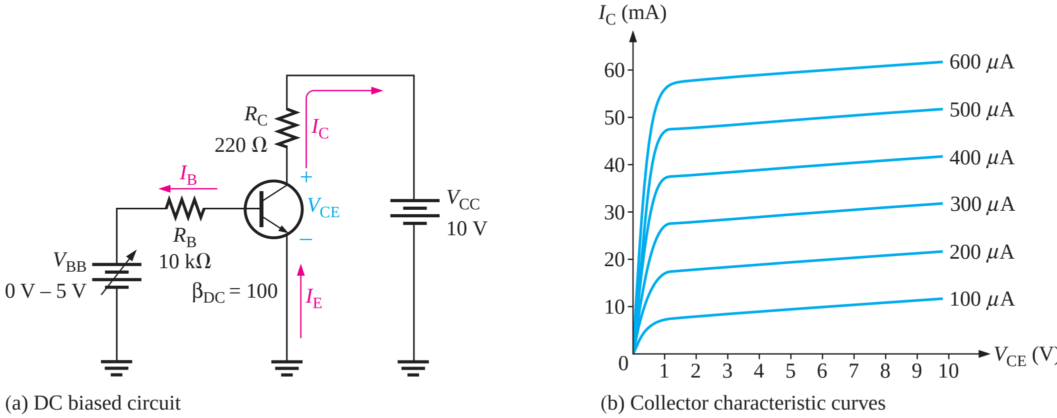
(b) Nonlinear operation: output voltage limited (clipped) by cutoff

(c) Nonlinear operation: output voltage limited (clipped) by saturation

▲ FIGURE 5–1

Examples of linear and nonlinear operation of an inverting amplifier (the triangle symbol).

Graphical Analysis The transistor in Figure 5–2(a) is biased with V_{CC} and V_{BB} to obtain certain values of I_B, I_C, I_E, and V_{CE}. The collector characteristic curves for this particular transistor are shown in Figure 5–2(b); we will use these curves to graphically illustrate the effects of dc bias.



▲ **FIGURE 5–2**

A dc-biased transistor circuit with variable bias voltage (V_{BB}) for generating the collector characteristic curves shown in part (b).

FYI

In 1965, a single transistor cost more than a dollar. By 1975, the cost of a transistor had dropped to less than a penny, while transistor size allowed for almost 100,000 transistors on a single chip. From 1979 to 1999, processor performance went from about 1.5 million instructions per second (MIPS) to over 1,000 MIPS. Today's processors, some topping out at well above one billion transistors, run at 3.2 GHz and higher, deliver over 10,000 MIPS, and can be manufactured in high volumes with transistors that cost less than 1/10,000th of a cent.

In Figure 5–3, we assign three values to I_B and observe what happens to I_C and V_{CE}. First, V_{BB} is adjusted to produce an I_B of 200 μA, as shown in Figure 5–3(a). Since $I_C = \beta_{DC} I_B$, the collector current is 20 mA, as indicated, and

$$V_{CE} = V_{CC} - I_C R_C = 10\text{ V} - (20\text{ mA})(220\ \Omega) = 10\text{ V} - 4.4\text{ V} = 5.6\text{ V}$$

This Q-point is shown on the graph of Figure 5–3(a) as Q_1.

Next, as shown in Figure 5–3(b), V_{BB} is increased to produce an I_B of 300 μA and an I_C of 30 mA.

$$V_{CE} = 10\text{ V} - (30\text{ mA})(220\ \Omega) = 10\text{ V} - 6.6\text{ V} = 3.4\text{ V}$$

The Q-point for this condition is indicated by Q_2 on the graph.

Finally, as in Figure 5–3(c), V_{BB} is increased to give an I_B of 400 μA and an I_C of 40 mA.

$$V_{CE} = 10\text{ V} - (40\text{ mA})(220\ \Omega) = 10\text{ V} - 8.8\text{ V} = 1.2\text{ V}$$

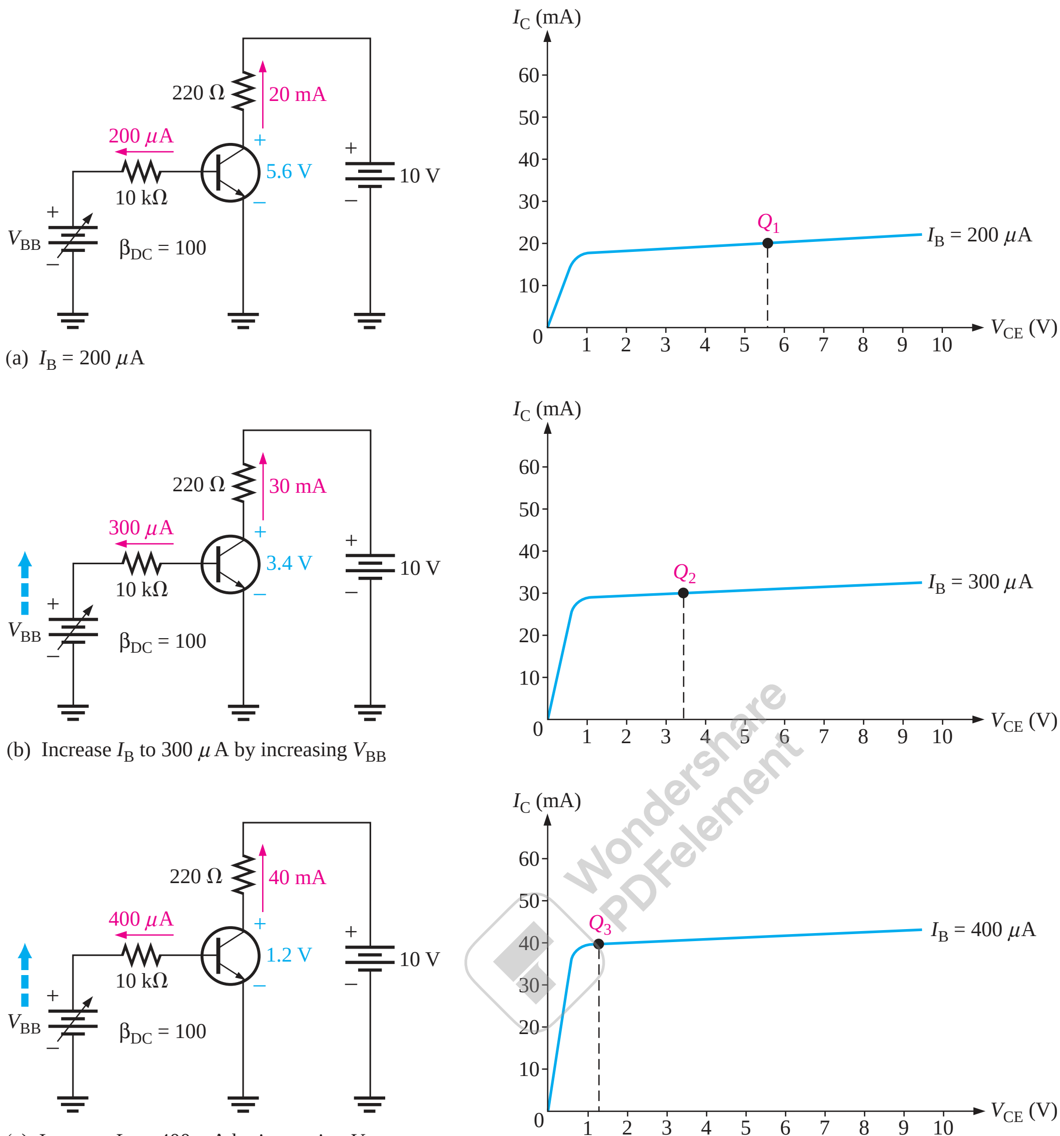
Q_3 is the corresponding Q-point on the graph.

DC Load Line The dc operation of a transistor circuit can be described graphically using a **dc load line**. This is a straight line drawn on the characteristic curves from the saturation value where $I_C = I_{C(sat)}$ on the *y*-axis to the cutoff value where $V_{CE} = V_{CC}$ on the *x*-axis, as shown in Figure 5–4(a). The load line is determined by the external circuit (V_{CC} and R_C), not the transistor itself, which is described by the characteristic curves.

In Figure 5–3, the equation for I_C is

$$I_C = \frac{V_{CC} - V_{CE}}{R_C} = \frac{V_{CC}}{R_C} - \frac{V_{CE}}{R_C} = -\frac{V_{CE}}{R_C} + \frac{V_{CC}}{R_C} = -\left(\frac{1}{R_C}\right)V_{CE} + \frac{V_{CC}}{R_C}$$

This is the equation of a straight line with a slope of $-1/R_C$, an *x* intercept of $V_{CE} = V_{CC}$, and a *y* intercept of V_{CC}/R_C, which is $I_{C(sat)}$.



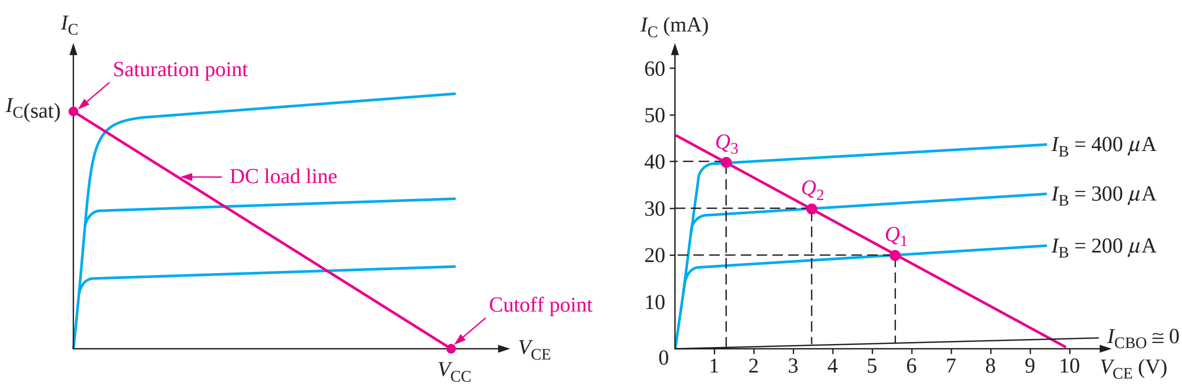
(a) I_B = 200 μA

(b) Increase I_B to 300 μA by increasing V_{BB}

(c) Increase I_B to 400 μA by increasing V_{BB}

▲ **FIGURE 5–3**

Illustration of Q-point adjustment.



(a) (b)

▲ **FIGURE 5–4**

The dc load line.

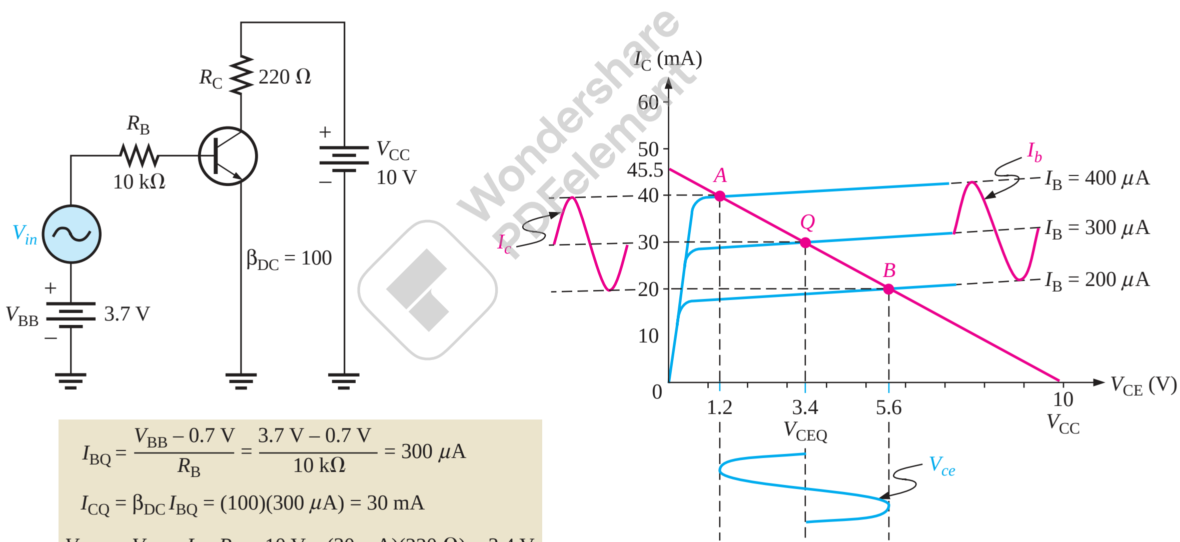
F Y I

Gordon Moore, one of the founders of Intel, observed in an article in the April, 1965, issue of *Electronics* magazine that innovations in technology would allow a doubling of the number of transistors in a given space every year (in an update article in 1975, Moore adjusted the rate to every two years to account for the growing complexity of chips), and that the speed of those transistors would increase. This prediction has become widely known as Moore's law.

The point at which the load line intersects a characteristic curve represents the Q-point for that particular value of I_B. Figure 5–4(b) illustrates the Q-point on the load line for each value of I_B in Figure 5–3.

Linear Operation The region along the load line including all points between saturation and cutoff is generally known as the **linear region** of the transistor's operation. As long as the transistor is operated in this region, the output voltage is ideally a linear reproduction of the input.

Figure 5–5 shows an example of the linear operation of a transistor. AC quantities are indicated by lowercase italic subscripts. Assume a sinusoidal voltage, V_{in}, is superimposed on V_{BB}, causing the base current to vary sinusoidally 100 μA above and below its Q-point value of 300 μA. This, in turn, causes the collector current to vary 10 mA above and below its Q-point value of 30 mA. As a result of the variation in collector current, the collector-to-emitter voltage varies 2.2 V above and below its Q-point value of 3.4 V. Point *A* on the load line in Figure 5–5 corresponds to the positive peak of the sinusoidal input voltage. Point *B* corresponds to the negative peak, and point *Q* corresponds to the zero value of the sine wave, as indicated. V_{CEQ}, I_{CQ}, and I_{BQ} are dc Q-point values with no input sinusoidal voltage applied.



$$I_{BQ} = \frac{V_{BB} - 0.7\text{ V}}{R_B} = \frac{3.7\text{ V} - 0.7\text{ V}}{10\text{ k}\Omega} = 300\ \mu\text{A}$$

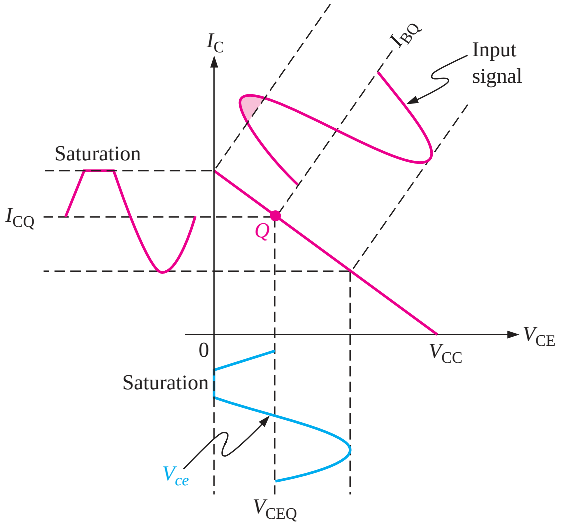
$$I_{CQ} = \beta_{DC} I_{BQ} = (100)(300\ \mu\text{A}) = 30\text{ mA}$$

$$V_{CEQ} = V_{CC} - I_{CQ}R_C = 10\text{ V} - (30\text{ mA})(220\ \Omega) = 3.4\text{ V}$$

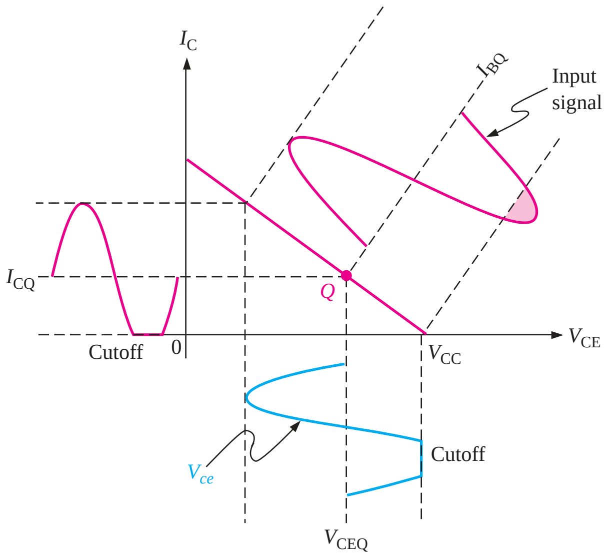
▲ **FIGURE 5–5**

Variations in collector current and collector-to-emitter voltage as a result of a variation in base current.

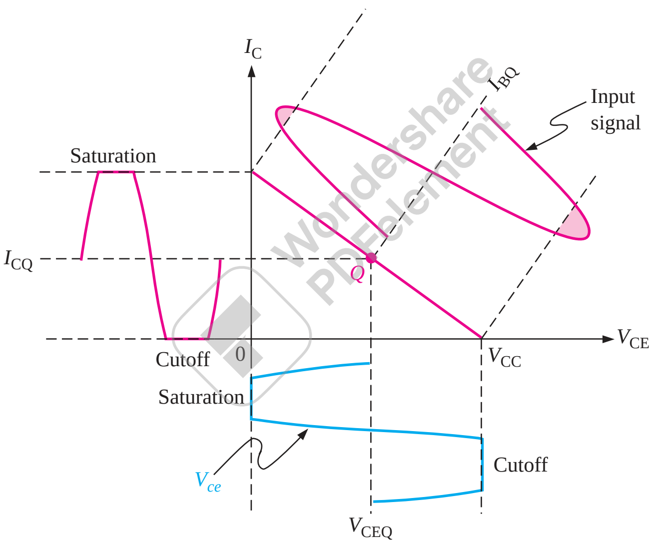
Waveform Distortion As previously mentioned, under certain input signal conditions the location of the Q-point on the load line can cause one peak of the V_{ce} waveform to be limited or clipped, as shown in parts (a) and (b) of Figure 5–6. In each case the input signal is too large for the Q-point location and is driving the transistor into cutoff or saturation during a portion of the input cycle. When both peaks are limited as in Figure 5–6(c), the transistor is being driven into both saturation and cutoff by an excessively large input signal. When only the positive peak is limited, the transistor is being driven into cutoff but not saturation. When only the negative peak is limited, the transistor is being driven into saturation but not cutoff.



(a) Transistor is driven into saturation because the Q-point is too close to saturation for the given input signal.



(b) Transistor is driven into cutoff because the Q-point is too close to cutoff for the given input signal.



(c) Transistor is driven into both saturation and cutoff because the input signal is too large.

▲ **FIGURE 5–6**

Graphical load line illustration of a transistor being driven into saturation and/or cutoff.

EXAMPLE 5–1

Determine the Q-point for the circuit in Figure 5–7 and draw the dc load line. Find the maximum peak value of base current for linear operation. Assume $\beta_{DC} = 200$.

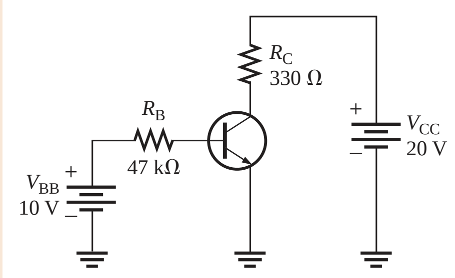
Solution The Q-point is defined by the values of I_C and V_{CE}.

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{10\text{ V} - 0.7\text{ V}}{47\text{ k}\Omega} = 198\ \mu\text{A}$$

$$I_C = \beta_{DC} I_B = (200)(198\ \mu\text{A}) = \mathbf{39.6\ mA}$$

$$V_{CE} = V_{CC} - I_C R_C = 20\text{ V} - 13.07\text{ V} = \mathbf{6.93\ V}$$

▶ FIGURE 5–7



The Q-point is at $I_C = 39.6$ mA and at $V_{CE} = 6.93$ V.

Since $I_{C(cutoff)} = 0$, you need to know $I_{C(sat)}$ to determine how much variation in collector current can occur and still maintain linear operation of the transistor.

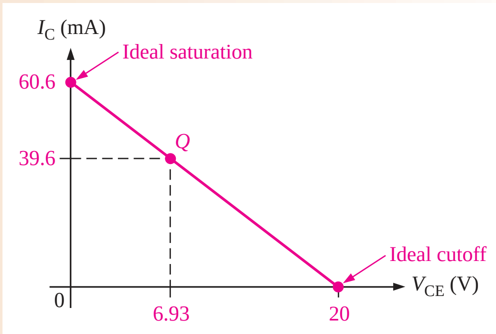
$$I_{C(sat)} = \frac{V_{CC}}{R_C} = \frac{20\text{ V}}{330\ \Omega} = 60.6\text{ mA}$$

The dc load line is graphically illustrated in Figure 5–8, showing that before saturation is reached, I_C can increase an amount ideally equal to

$$I_{C(sat)} - I_{CQ} = 60.6\text{ mA} - 39.6\text{ mA} = 21.0\text{ mA}$$

However, I_C can decrease by 39.6 mA before cutoff ($I_C = 0$) is reached. Therefore, the limiting excursion is 21 mA because the *Q-point is closer to saturation than to cutoff*. The 21 mA is the maximum peak variation of the collector current. Actually, it would be slightly less in practice because $V_{CE(sat)}$ is not quite zero.

▶ FIGURE 5–8



Determine the maximum peak variation of the base current as follows:

$$I_{b(peak)} = \frac{I_{c(peak)}}{\beta_{DC}} = \frac{21\text{ mA}}{200} = \mathbf{105\ \mu A}$$

Related Problem[*] Find the Q-point for the circuit in Figure 5–7, and determine the maximum peak value of base current for linear operation for the following circuit values: $\beta_{DC} = 100$, $R_C = 1.0\text{ k}\Omega$, and $V_{CC} = 24$ V.

[*] **Answers can be found at www.pearsonhighered.com/floyd.**

Open the Multisim file E05-01 in the Examples folder on the companion website. Measure I_C and V_{CE} and compare with the calculated values.

SECTION 5–1 CHECKUP
Answers can be found at www.pearsonhighered.com/floyd.

1. What are the upper and lower limits on a dc load line in terms of V_{CE} and I_C?
2. Define *Q-point*.
3. At what point on the load line does saturation occur? At what point does cutoff occur?
4. For maximum V_{ce}, where should the Q-point be placed?

5–2 VOLTAGE-DIVIDER BIAS

You will now study a method of biasing a transistor for linear operation using a single-source resistive voltage divider. This is the most widely used biasing method. Four other methods are covered in Section 5–3.

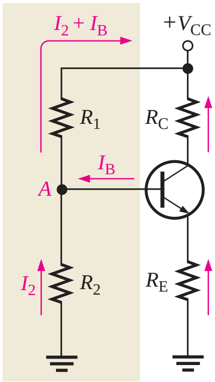
After completing this section, you should be able to

- **Analyze a voltage-divider biased circuit**
  ◆ Define the term *stiff voltage-divider* ◆ Calculate currents and voltages in a voltage-divider biased circuit
- Explain the loading effects in voltage-divider bias
  ◆ Describe how dc input resistance at the transistor base affects the bias
- Apply Thevenin's theorem to the analysis of voltage-divider bias
  ◆ Analyze both *npn* and *pnp* circuits

Up to this point a separate dc source, V_{BB}, was used to bias the base-emitter junction because it could be varied independently of V_{CC} and it helped to illustrate transistor operation. A more practical bias method is to use V_{CC} as the single bias source, as shown in Figure 5–9. To simplify the schematic, the battery symbol is omitted and replaced by a line termination circle with a voltage indicator (V_{CC}) as shown.

A dc bias voltage at the base of the transistor can be developed by a resistive voltage-divider that consists of R_1 and R_2, as shown in Figure 5–9. V_{CC} is the dc collector supply voltage. Two current paths are between point *A* and ground: one through R_2 and the other through the base-emitter junction of the transistor and R_E.

Generally, voltage-divider bias circuits are designed so that the base current is much smaller than the current (I_2) through R_2 in Figure 5–9. In this case, the voltage-divider circuit is very straightforward to analyze because the loading effect of the base current can be ignored. A voltage divider in which the base current is small compared to the current in R_2 is said to be a **stiff voltage divider** because the base voltage is relatively independent of different transistors and temperature effects.



▲ FIGURE 5–9
Voltage-divider bias.

To analyze a voltage-divider circuit in which I_B is small compared to I_2, first calculate the voltage on the base using the unloaded voltage-divider rule:

$$V_B \cong \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} \quad \text{Equation 5–1}$$

Once you know the base voltage, you can find the voltages and currents in the circuit, as follows:

$$V_E = V_B - V_{BE} \quad \text{Equation 5–2}$$

and

$$I_C \cong I_E = \frac{V_E}{R_E} \quad \text{Equation 5–3}$$

Then,

$$V_C = V_{CC} - I_C R_C \quad \text{Equation 5–4}$$

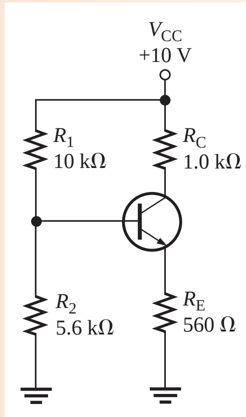
Once you know V_C and V_E, you can determine V_{CE}.

$$V_{CE} = V_C - V_E$$

EXAMPLE 5–2

Determine V_{CE} and I_C in the stiff voltage-divider biased transistor circuit of Figure 5–10 if $\beta_{DC} = 100$.

▶ **FIGURE 5–10**



Solution The base voltage is

$$V_B \cong \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\frac{5.6\text{ k}\Omega}{15.6\text{ k}\Omega}\right)10\text{ V} = 3.59\text{ V}$$

So,

$$V_E = V_B - V_{BE} = 3.59\text{ V} - 0.7\text{ V} = 2.89\text{ V}$$

and

$$I_E = \frac{V_E}{R_E} = \frac{2.89\text{ V}}{560\ \Omega} = 5.16\text{ mA}$$

Therefore,

$$I_C \cong I_E = \mathbf{5.16\text{ mA}}$$

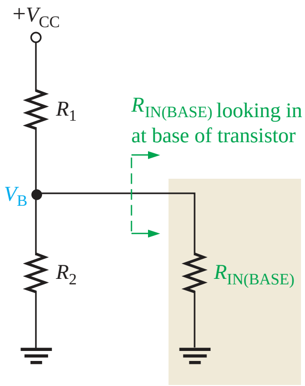
and

$$V_C = V_{CC} - I_C R_C = 10\text{ V} - (5.16\text{ mA})(1.0\text{ k}\Omega) = 4.84\text{ V}$$
$$V_{CE} = V_C - V_E = 4.84\text{ V} - 2.89\text{ V} = \mathbf{1.95\text{ V}}$$

Related Problem If the voltage divider in Figure 5–10 was not stiff, how would V_B be affected?

Open the Multisim file E05-02 in the Examples folder on the companion website. Measure I_C and V_{CE}. If these results do not agree very closely with those in the Example, what original assumption was incorrect?

The basic analysis developed in Example 5–2 is all that is needed for most voltage-divider circuits, but there may be cases where you need to analyze the circuit with more accuracy. Ideally, a voltage-divider circuit is stiff, which means that the transistor does not appear as a significant load. All circuit design involves trade-offs; and one trade-off is that stiff voltage dividers require smaller resistors, which are not always desirable because of potential loading effects on other circuits and added power requirements. If the circuit designer wanted to raise the input resistance, the divider string may not be stiff; and more detailed analysis is required to calculate circuit parameters. To determine if the divider is stiff, you need to examine the dc input resistance looking in at the base as shown in Figure 5–11.



Stiff:

$R_{IN(BASE)} \geqq 10R_2$

$V_B \cong \left(\frac{R_2}{R_1 + R_2}\right) V_{CC}$

Not stiff:

$R_{IN(BASE)} < 10R_2$

$V_B = \left(\frac{R_2 \parallel R_{IN(BASE)}}{R_1 + R_2 \parallel R_{IN(BASE)}}\right) V_{CC}$

◀ **FIGURE 5–11**

Voltage divider with load.

Loading Effects of Voltage-Divider Bias

DC Input Resistance at the Transistor Base The dc input resistance of the transistor is proportional to β_{DC}, so it will change for different transistors. When a transistor is operating in its linear region, the emitter current (I_E) is $\beta_{DC}I_B$. When the emitter resistor is viewed from the base circuit, the resistor appears to be larger than its actual value because of the dc current gain in the transistor. That is, $R_{IN(BASE)} = V_B/I_B = V_B/(I_E/\beta_{DC})$.

$$R_{IN(BASE)} = \frac{\beta_{DC}V_B}{I_E} \qquad \textbf{Equation 5–5}$$

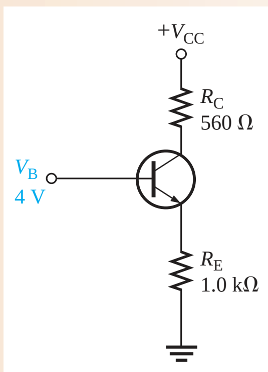
This is the effective load on the voltage divider illustrated in Figure 5–11.

You can quickly estimate the loading effect by comparing $R_{IN(BASE)}$ to the resistor R_2 in the voltage divider. As long as $R_{IN(BASE)}$ is at least ten times larger than R_2, the loading effect will be 10% or less and the voltage divider is stiff. If $R_{IN(BASE)}$ is less than ten times R_2, it should be combined in parallel with R_2.

EXAMPLE 5–3

Determine the dc input resistance looking in at the base of the transistor in Figure 5–12. $\beta_{DC} = 125$ and $V_B = 4$ V.

▶ **FIGURE 5–12**



Solution

$$I_E = \frac{V_B - 0.7\text{ V}}{R_E} = \frac{3.3\text{ V}}{1.0\text{ k}\Omega} = 3.3\text{ mA}$$

$$R_{IN(BASE)} = \frac{\beta_{DC}V_B}{I_E} = \frac{125(4\text{ V})}{3.3\text{ mA}} = \mathbf{152\text{ k}\Omega}$$

Related Problem What is $R_{IN(BASE)}$ in Figure 5–12 if $\beta_{DC} = 60$ and $V_B = 2$ V?

Thevenin's Theorem Applied to Voltage-Divider Bias

To analyze a voltage-divider biased transistor circuit for base current loading effects, we will apply Thevenin's theorem to evaluate the circuit. First, let's get an equivalent base-emitter circuit for the circuit in Figure 5–13(a) using Thevenin's theorem. Looking out from the base terminal, the bias circuit can be redrawn as shown in Figure 5–13(b). Apply Thevenin's theorem to the circuit left of point *A*, with V_{CC} replaced by a short to ground and the transistor disconnected from the circuit. The voltage at point *A* with respect to ground is

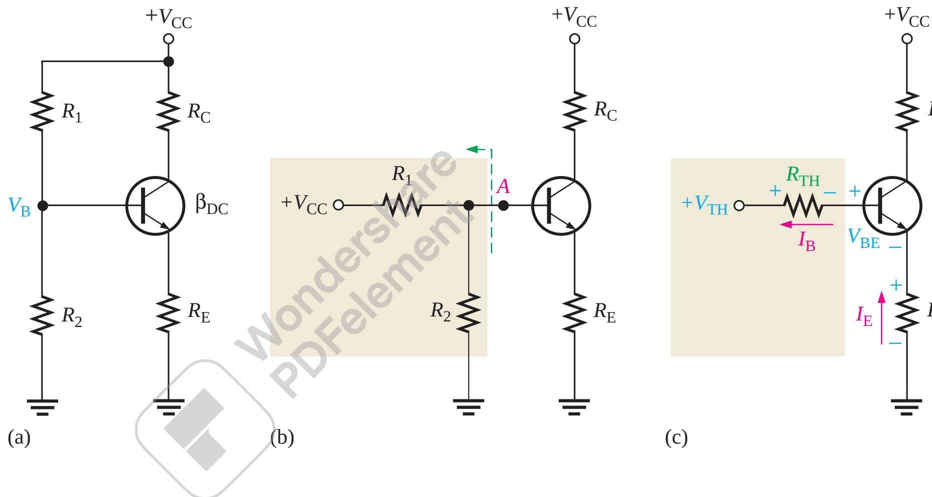
$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC}$$

and the resistance is

$$R_{TH} = \frac{R_1R_2}{R_1 + R_2}$$

▶ **FIGURE 5–13**

Thevenizing the bias circuit.



The Thevenin equivalent of the bias circuit, connected to the transistor base, is shown in the beige box in Figure 5–13(c). Applying Kirchhoff's voltage law around the equivalent base-emitter loop gives

$$V_{TH} - V_{R_{TH}} - V_{BE} - V_{R_E} = 0$$

Substituting, using Ohm's law, and solving for V_{TH},

$$V_{TH} = I_BR_{TH} + V_{BE} + I_ER_E$$

Substituting I_E/β_{DC} for I_B,

$$V_{TH} = I_E(R_E + R_{TH}/\beta_{DC}) + V_{BE}$$

Then solving for I_E,

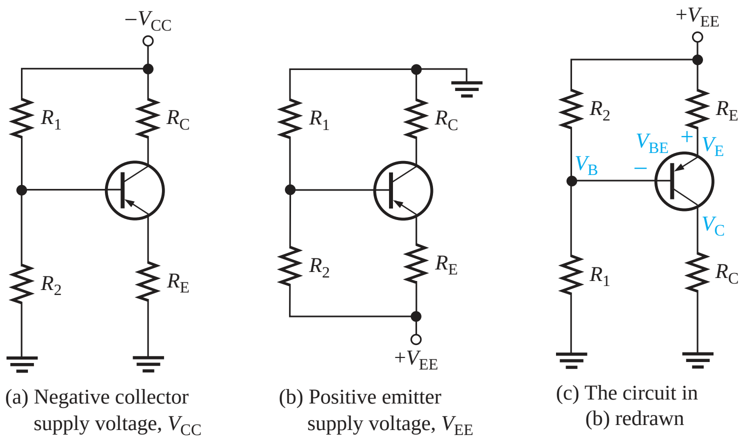
Equation 5–6

$$\boldsymbol{I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}}}$$

If R_{TH}/β_{DC} is small compared to R_E, the result is the same as for an unloaded voltage divider.

Voltage-divider bias is widely used because reasonably good bias stability is achieved with a single supply voltage.

Voltage-Divider Biased PNP Transistor As you know, a *pnp* transistor requires bias polarities opposite to the *npn*. This can be accomplished with a negative collector supply voltage, as in Figure 5–14(a), or with a positive emitter supply voltage, as in Figure 5–14(b).



▲ **FIGURE 5–14**

Voltage-divider biased *pnp* transistor.

In a schematic, the *pnp* is often drawn upside down so that the supply voltage is at the top of the schematic and ground at the bottom, as in Figure 5–14(c).

The analysis procedure is the same as for an *npn* transistor circuit using Thevenin's theorem and Kirchhoff's voltage law, as demonstrated in the following steps with reference to Figure 5–14. For Figure 5–14(a), applying Kirchhoff's voltage law around the base-emitter circuit gives

$$V_{TH} + I_B R_{TH} - V_{BE} + I_E R_E = 0$$

By Thevenin's theorem,

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC}$$

$$R_{TH} = \frac{R_1 R_2}{R_1 + R_2}$$

The base current is

$$I_B = \frac{I_E}{\beta_{DC}}$$

The equation for I_E is

$$\mathbf{I_E = \frac{-V_{TH} + V_{BE}}{R_E + R_{TH}/\beta_{DC}}}$$ **Equation 5–7**

For Figure 5–14(b), the analysis is as follows:

$$-V_{TH} + I_B R_{TH} - V_{BE} + I_E R_E - V_{EE} = 0$$

$$V_{TH} = \left(\frac{R_1}{R_1 + R_2}\right)V_{EE}$$

$$R_{TH} = \frac{R_1 R_2}{R_1 + R_2}$$

$$I_B = \frac{I_E}{\beta_{DC}}$$

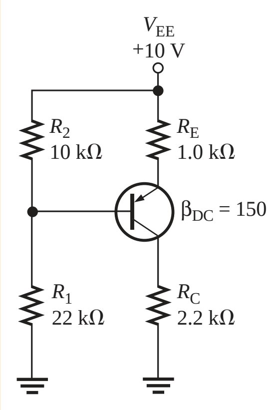
The equation for I_E is

$$\mathbf{I_E = \frac{V_{TH} + V_{BE} - V_{EE}}{R_E + R_{TH}/\beta_{DC}}}$$ **Equation 5–8**

EXAMPLE 5–4

Find I_C and V_{EC} for the *pnp* transistor circuit in Figure 5–15.

▶ **FIGURE 5–15**



Solution This circuit has the configuration of Figures 5–14(b) and (c). Apply Thevenin's theorem.

$$V_{TH} = \left(\frac{R_1}{R_1 + R_2}\right)V_{EE} = \left(\frac{22\text{ k}\Omega}{22\text{ k}\Omega + 10\text{ k}\Omega}\right)10\text{ V} = (0.688)10\text{ V} = 6.88\text{ V}$$

$$R_{TH} = \frac{R_1R_2}{R_1 + R_2} = \frac{(22\text{ k}\Omega)(10\text{ k}\Omega)}{22\text{ k}\Omega + 10\text{ k}\Omega} = 6.88\text{ k}\Omega$$

Use Equation 5–8 to determine I_E.

$$I_E = \frac{V_{TH} + V_{BE} - V_{EE}}{R_E + R_{TH}/\beta_{DC}} = \frac{6.88\text{ V} + 0.7\text{ V} - 10\text{ V}}{1.0\text{ k}\Omega + 45.9\text{ }\Omega} = \frac{-2.42\text{ V}}{1.0459\text{ k}\Omega} = -2.31\text{ mA}$$

The negative sign on I_E indicates that the assumed current direction in the Kirchhoff's analysis is opposite from the actual current direction. From I_E, you can determine I_C and V_{EC} as follows:

$$I_C = I_E = \mathbf{2.31\text{ mA}}$$

$$V_C = I_CR_C = (2.31\text{ mA})(2.2\text{ k}\Omega) = 5.08\text{ V}$$

$$V_E = V_{EE} - I_ER_E = 10\text{ V} - (2.31\text{ mA})(1.0\text{ k}\Omega) = 7.68\text{ V}$$

$$V_{EC} = V_E - V_C = 7.68\text{ V} - 5.08\text{ V} = \mathbf{2.6\text{ V}}$$

Related Problem Determine $R_{IN(BASE)}$ for Figure 5–15.

Open the Multisim file E05-04 in the Examples folder on the companion website. Measure I_C and V_{EC}.

EXAMPLE 5–5

Find I_C and V_{CE} for a *pnp* transistor circuit with these values: $R_1 = 68\text{ k}\Omega$, $R_2 = 47\text{ k}\Omega$, $R_C = 1.8\text{ k}\Omega$, $R_E = 2.2\text{ k}\Omega$, $V_{CC} = -6\text{ V}$, and $\beta_{DC} = 75$. Refer to Figure 5–14(a), which shows the schematic with a negative supply voltage.

Solution Apply Thevenin's theorem.

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\frac{47\text{ k}\Omega}{68\text{ k}\Omega + 47\text{ k}\Omega}\right)(-6\text{ V})$$

$$= (0.409)(-6\text{ V}) = -2.45\text{ V}$$

$$R_{TH} = \frac{R_1R_2}{R_1 + R_2} = \frac{(68\text{ k}\Omega)(47\text{ k}\Omega)}{(68\text{ k}\Omega + 47\text{ k}\Omega)} = 27.8\text{ k}\Omega$$

Use Equation 5–7 to determine I_E.

$$I_E = \frac{-V_{TH} + V_{BE}}{R_E + R_{TH}/\beta_{DC}} = \frac{2.45\text{ V} + 0.7\text{ V}}{2.2\text{ k}\Omega + 371\ \Omega}$$

$$= \frac{3.15\text{ V}}{2.57\text{ k}\Omega} = 1.23\text{ mA}$$

From I_E, you can determine I_C and V_{CE} as follows:

$$I_C = I_E = \mathbf{1.23\text{ mA}}$$

$$V_C = -V_{CC} + I_CR_C = -6\text{ V} + (1.23\text{ mA})(1.8\text{ k}\Omega) = -3.79\text{ V}$$

$$V_E = -I_ER_E = -(1.23\text{ mA})(2.2\text{ k}\Omega) = -2.71\text{ V}$$

$$V_{CE} = V_C - V_E = -3.79\text{ V} + 2.71\text{ V} = \mathbf{-1.08\text{ V}}$$

Related Problem What value of β_{DC} is required in this example in order to neglect $R_{IN(BASE)}$ in keeping with the basic ten-times rule for a stiff voltage divider?

SECTION 5–2 CHECKUP

1. If the voltage at the base of a transistor is 5 V and the base current is 5 μA, what is the dc input resistance at the base?
2. If a transistor has a dc beta of 190, V_B = 2 V, and I_E = 2 mA, what is the dc input resistance at the base?
3. What bias voltage is developed at the base of a transistor if both resistors in a stiff voltage divider are equal and V_{CC} = +10 V?
4. What are two advantages of voltage-divider bias?

5–3 OTHER BIAS METHODS

In this section, four additional methods for dc biasing a transistor circuit are discussed. Although these methods are not as common as voltage-divider bias, you should be able to recognize them when you see them and understand the basic differences.

After completing this section, you should be able to

- **Analyze four more types of bias circuits**
- Discuss emitter bias
  - Analyze an emitter-biased circuit
- Discuss base bias
  - Analyze a base-biased circuit ◆ Explain Q-point stability of base bias
- Discuss emitter-feedback bias
  - Define negative feedback ◆ Analyze an emitter-feedback biased circuit
- Discuss collector-feedback bias
  - Analyze a collector-feedback biased circuit ◆ Discuss Q-point stability over temperature

Emitter Bias

Emitter bias provides excellent bias stability in spite of changes in β or temperature. It uses both a positive and a negative supply voltage. To obtain a reasonable estimate of the key dc values in an emitter-biased circuit, analysis is quite easy. In an *npn* circuit, such as shown in Figure 5–17, the small base current causes the base voltage to be slightly below ground. The emitter voltage is one diode drop less than this. The combination of this small drop across R_B and V_{BE} forces the emitter to be at approximately -1 V. Using this approximation, you can obtain the emitter current as

$$I_E = \frac{-V_{EE} - 1\text{ V}}{R_E}$$

V_{EE} is entered as a negative value in this equation.

You can apply the approximation that $I_C \cong I_E$ to calculate the collector voltage.

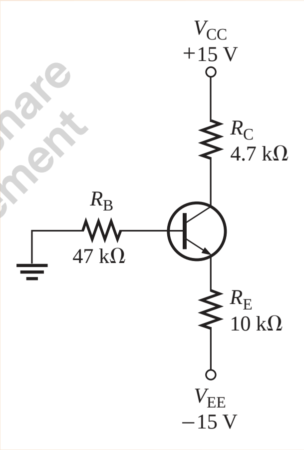
$$V_C = V_{CC} - I_C R_C$$

The approximation that $V_E \cong -1$ V is useful for troubleshooting because you won't need to perform any detailed calculations. As in the case of voltage-divider bias, there is a more rigorous calculation for cases where you need a more exact result.

EXAMPLE 5–6

Calculate I_E and V_{CE} for the circuit in Figure 5–16 using the approximations $V_E \cong -1$ V and $I_C \cong I_E$.

▶ FIGURE 5–16



Solution

$$V_E \cong -1\text{ V}$$

$$I_E = \frac{-V_{EE} - 1\text{ V}}{R_E} = \frac{-(-15\text{ V}) - 1\text{ V}}{10\text{ k}\Omega} = \frac{14\text{ V}}{10\text{ k}\Omega} = \mathbf{1.4\text{ mA}}$$

$$V_C = V_{CC} - I_C R_C = +15\text{ V} - (1.4\text{ mA})(4.7\text{ k}\Omega) = 8.4\text{ V}$$

$$V_{CE} = 8.4\text{ V} - (-1) = \mathbf{9.4\text{ V}}$$

Related Problem If V_{EE} is changed to -12 V, what is the new value of V_{CE}?

The approximation that $V_E \cong -1$ V and the neglect of β_{DC} may not be accurate enough for design work or detailed analysis. In this case, Kirchhoff's voltage law can be applied as follows to develop a more detailed formula for I_E. Kirchhoff's voltage law applied around the base-emitter circuit in Figure 5–17(a), which has been redrawn in part (b) for analysis, gives the following equation:

$$V_{EE} + V_{R_B} + V_{BE} + V_{R_E} = 0$$

Substituting, using Ohm's law,

$$V_{EE} + I_B R_B + V_{BE} + I_E R_E = 0$$

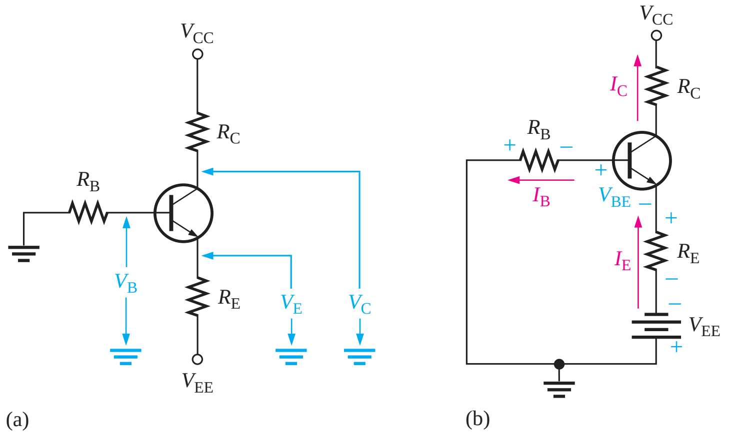


FIGURE 5–17

An *npn* transistor with emitter bias. Polarities are reversed for a *pnp* transistor. Single subscripts indicate voltages with respect to ground.

Substituting for $I_B \cong I_E/\beta_{DC}$ and transposing V_{EE},

$$\left(\frac{I_E}{\beta_{DC}}\right)R_B + I_ER_E + V_{BE} = -V_{EE}$$

Factoring out I_E and solving for I_E,

$$\mathbf{I_E = \frac{-V_{EE} - V_{BE}}{R_E + R_B/\beta_{DC}}}$$

Equation 5–9

Voltages with respect to ground are indicated by a single subscript. The emitter voltage with respect to ground is

$$V_E = V_{EE} + I_ER_E$$

The base voltage with respect to ground is

$$V_B = V_E + V_{BE}$$

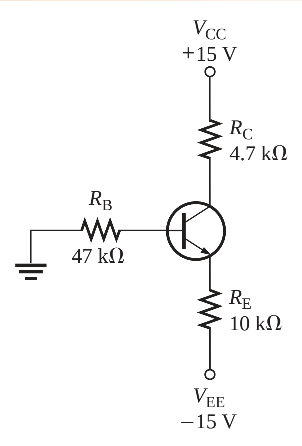
The collector voltage with respect to ground is

$$V_C = V_{CC} - I_CR_C$$

EXAMPLE 5–7

Determine how much the Q-point (I_C, V_{CE}) for the circuit in Figure 5–18 will change if β_{DC} increases from 100 to 200 when one transistor is replaced by another.

FIGURE 5–18



Solution For $\beta_{DC} = 100$,

$$I_{C(1)} \cong I_E = \frac{-V_{EE} - V_{BE}}{R_E + R_B/\beta_{DC}} = \frac{-(-15\text{ V}) - 0.7\text{ V}}{10\text{ k}\Omega + 47\text{ k}\Omega/100} = 1.37\text{ mA}$$

$$V_C = V_{CC} - I_{C(1)}R_C = 15\text{ V} - (1.37\text{ mA})(4.7\text{ k}\Omega) = 8.56\text{ V}$$

$$V_E = V_{EE} + I_E R_E = -15\text{ V} + (1.37\text{ mA})(10\text{ k}\Omega) = -1.3\text{ V}$$

Therefore,

$$V_{CE(1)} = V_C - V_E = 8.56\text{ V} - (-1.3\text{ V}) = 9.83\text{ V}$$

For $\beta_{DC} = 200$,

$$I_{C(2)} \cong I_E = \frac{-V_{EE} - V_{BE}}{R_E + R_B/\beta_{DC}} = \frac{-(-15\text{ V}) - 0.7\text{ V}}{10\text{ k}\Omega + 47\text{ k}\Omega/200} = 1.38\text{ mA}$$

$$V_C = V_{CC} - I_{C(2)}R_C = 15\text{ V} - (1.38\text{ mA})(4.7\text{ k}\Omega) = 8.51\text{ V}$$

$$V_E = V_{EE} + I_E R_E = -15\text{ V} + (1.38\text{ mA})(10\text{ k}\Omega) = -1.2\text{ V}$$

Therefore,

$$V_{CE(2)} = V_C - V_E = 8.51\text{ V} - (-1.2\text{ V}) = 9.71\text{ V}$$

The percent change in I_C as β_{DC} changes from 100 to 200 is

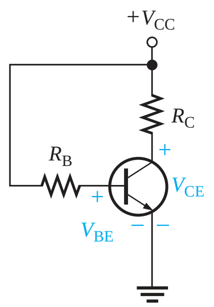
$$\%\Delta I_C = \left(\frac{I_{C(2)} - I_{C(1)}}{I_{C(1)}}\right)100\% = \left(\frac{1.38\text{ mA} - 1.37\text{ mA}}{1.37\text{ mA}}\right)100\% = 0.730\%$$

The percent change in V_{CE} is

$$\%\Delta V_{CE} = \left(\frac{V_{CE(2)} - V_{CE(1)}}{V_{CE(1)}}\right)100\% = \left(\frac{9.71\text{ V} - 9.83\text{ V}}{9.83\text{ V}}\right)100\% = \mathbf{-1.22\%}$$

Related Problem Determine the Q-point in Figure 5–18 if β_{DC} increases to 300.

Base Bias



▲ FIGURE 5–19

Base bias.

This method of biasing is common in switching circuits. Figure 5–19 shows a base-biased transistor. The analysis of this circuit for the linear region shows that it is directly dependent on β_{DC}. Starting with Kirchhoff's voltage law around the base circuit,

$$V_{CC} - V_{R_B} - V_{BE} = 0$$

Substituting $I_B R_B$ for V_{R_B}, you get

$$V_{CC} - I_B R_B - V_{BE} = 0$$

Then solving for I_B,

$$I_B = \frac{V_{CC} - V_{BE}}{R_B}$$

Kirchhoff's voltage law applied around the collector circuit in Figure 5–19 gives the following equation:

$$V_{CC} - I_C R_C - V_{CE} = 0$$

Solving for V_{CE},

Equation 5–10

$$\mathbf{V_{CE} = V_{CC} - I_C R_C}$$

Substituting the expression for I_B into the formula $I_C = \beta_{DC} I_B$ yields

Equation 5–11

$$\mathbf{I_C = \beta_{DC}\left(\frac{V_{CC} - V_{BE}}{R_B}\right)}$$

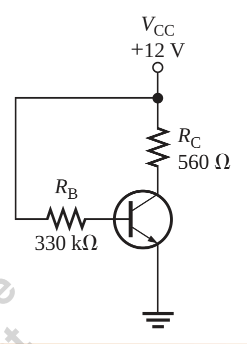
Q-Point Stability of Base Bias Notice that Equation 5–11 shows that I_C is dependent on β_{DC}. The disadvantage of this is that a variation in β_{DC} causes I_C and, as a result, V_{CE} to change, thus changing the Q-point of the transistor. This makes the base bias circuit extremely beta-dependent and unpredictable.

Recall that β_{DC} varies with temperature and collector current. In addition, there is a large spread of β_{DC} values from one transistor to another of the same type due to manufacturing variations. For these reasons, base bias is rarely used in linear circuits but is discussed here so you will be familiar with it.

EXAMPLE 5–8

Determine how much the Q-point (I_C, V_{CE}) for the circuit in Figure 5–20 will change over a temperature range where β_{DC} increases from 100 to 200.

► FIGURE 5–20



Solution For $\beta_{DC} = 100$,

$$I_{C(1)} = \beta_{DC}\left(\frac{V_{CC} - V_{BE}}{R_B}\right) = 100\left(\frac{12\text{ V} - 0.7\text{ V}}{330\text{ k}\Omega}\right) = 3.42\text{ mA}$$

$$V_{CE(1)} = V_{CC} - I_{C(1)}R_C = 12\text{ V} - (3.42\text{ mA})(560\ \Omega) = 10.1\text{ V}$$

For $\beta_{DC} = 200$,

$$I_{C(2)} = \beta_{DC}\left(\frac{V_{CC} - V_{BE}}{R_B}\right) = 200\left(\frac{12\text{ V} - 0.7\text{ V}}{330\text{ k}\Omega}\right) = 6.84\text{ mA}$$

$$V_{CE(2)} = V_{CC} - I_{C(2)}R_C = 12\text{ V} - (6.84\text{ mA})(560\ \Omega) = 8.17\text{ V}$$

The percent change in I_C as β_{DC} changes from 100 to 200 is

$$\%\Delta I_C = \left(\frac{I_{C(2)} - I_{C(1)}}{I_{C(1)}}\right)100\%$$

$$= \left(\frac{6.84\text{ mA} - 3.42\text{ mA}}{3.42\text{ mA}}\right)100\% = \mathbf{100\%}\text{ (an increase)}$$

The percent change in V_{CE} is

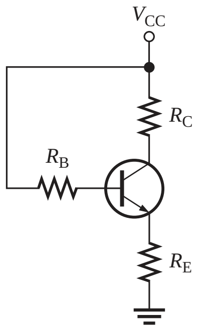
$$\%\Delta V_{CE} = \left(\frac{V_{CE(2)} - V_{CE(1)}}{V_{CE(1)}}\right)100\%$$

$$= \left(\frac{8.17\text{ V} - 10.1\text{ V}}{10.1\text{ V}}\right)100\% = \mathbf{-19.1\%}\text{ (a decrease)}$$

As you can see, the Q-point is very dependent on β_{DC} in this circuit and therefore makes the base bias arrangement very unreliable. Consequently, base bias is not normally used if linear operation is required. However, it can be used in switching applications.

Related Problem Determine I_C if β_{DC} increases to 300.

Open the Multisim file E05-08 in the Examples folder on the companion website. Set $\beta_{DC} = 100$ and measure I_C and V_{CE}. Next, set $\beta_{DC} = 200$ and measure I_C and V_{CE}. Compare results with the calculated values.



▲ **FIGURE 5–21**

Emitter-feedback bias.

Emitter-Feedback Bias

If an emitter resistor is added to the base-bias circuit in Figure 5–20, the result is emitter-feedback bias, as shown in Figure 5–21. The idea is to help make base bias more predictable with negative **feedback**, which negates any attempted change in collector current with an opposing change in base voltage. If the collector current tries to increase, the emitter voltage increases, causing an increase in base voltage because $V_B = V_E + V_{BE}$. This increase in base voltage reduces the voltage across R_B, thus reducing the base current and keeping the collector current from increasing. A similar action occurs if the collector current tries to decrease. While this is better for linear circuits than base bias, it is still dependent on β_{DC} and is not as predictable as voltage-divider bias. To calculate I_E, you can write Kirchhoff's voltage law (KVL) around the base circuit.

$$-V_{CC} + I_B R_B + V_{BE} + I_E R_E = 0$$

Substituting I_E/β_{DC} for I_B, you can see that I_E is still dependent on β_{DC}.

Equation 5–12

$$\mathbf{I_E = \frac{V_{CC} - V_{BE}}{R_E + R_B/\beta_{DC}}}$$

EXAMPLE 5–9

The base-bias circuit from Example 5–8 is converted to emitter-feedback bias by the addition of a 1 kΩ emitter resistor. All other values are the same, and a transistor with a $\beta_{DC} = 100$ is used. Determine how much the Q-point will change if the first transistor is replaced with one having a $\beta_{DC} = 200$. Compare the results to those of the base-bias circuit.

Solution For $\beta_{DC} = 100$,

$$I_{C(1)} = I_E = \frac{V_{CC} - V_{BE}}{R_E + R_B/\beta_{DC}} = \frac{12\text{ V} - 0.7\text{ V}}{1\text{ k}\Omega + 330\text{ k}\Omega/100} = 2.63\text{ mA}$$

$$V_{CE(1)} = V_{CC} - I_{C(1)}(R_C + R_E) = 12\text{ V} - (2.63\text{ mA})(560\ \Omega + 1\text{ k}\Omega) = 7.90\text{ V}$$

For $\beta_{DC} = 200$,

$$I_{C(2)} = I_E = \frac{V_{CC} - V_{BE}}{R_E + R_B/\beta_{DC}} = \frac{12\text{ V} - 0.7\text{ V}}{1\text{ k}\Omega + 330\text{ k}\Omega/200} = 4.26\text{ mA}$$

$$V_{CE(2)} = V_{CC} - I_{C(2)}(R_C + R_E) = 12\text{ V} - (4.26\text{ mA})(560\ \Omega + 1\text{ k}\Omega) = 5.35\text{ V}$$

The percent change in I_C is

$$\%\Delta I_C = \left(\frac{I_{C(2)} - I_{C(1)}}{I_{C(1)}}\right)100\% = \left(\frac{4.26\text{ mA} - 2.63\text{ mA}}{2.63\text{ mA}}\right)100\% = \mathbf{62.0\%}$$

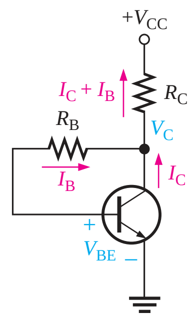
$$\%\Delta V_{CE} = \left(\frac{V_{CE(2)} - V_{CE(1)}}{V_{CE(1)}}\right)100\% = \left(\frac{7.90\text{ V} - 5.35\text{ V}}{7.90\text{ V}}\right)100\% = \mathbf{-32.3\%}$$

Although the emitter-feedback bias significantly improved the stability of the bias for a change in β_{DC} compared to base bias, it still does not provide a reliable Q-point.

Related Problem Determine I_C if a transistor with $\beta_{DC} = 300$ is used in the circuit.

Collector-Feedback Bias

In Figure 5–22, the base resistor R_B is connected to the collector rather than to V_{CC}, as it was in the base bias arrangement discussed earlier. The collector voltage provides the bias for the base-emitter junction. The negative feedback creates an "offsetting" effect that tends to keep the Q-point stable. If I_C tries to increase, it drops more voltage across R_C, thereby causing V_C to decrease. When V_C decreases, there is a decrease in voltage across R_B, which decreases I_B. The decrease in I_B produces less I_C which, in turn, drops less voltage across R_C and thus offsets the decrease in V_C.



▲ FIGURE 5–22

Collector-feedback bias.

Analysis of a Collector-Feedback Bias Circuit By Ohm's law, the base current can be expressed as

$$I_B = \frac{V_C - V_{BE}}{R_B}$$

Let's assume that $I_C \gg I_B$. The collector voltage is

$$V_C \cong V_{CC} - I_C R_C$$

Also,

$$I_B = \frac{I_C}{\beta_{DC}}$$

Substituting for V_C in the equation $I_B = (V_C - V_{BE})/R_B$,

$$\frac{I_C}{\beta_{DC}} = \frac{V_{CC} - I_C R_C - V_{BE}}{R_B}$$

The terms can be arranged so that

$$\frac{I_C R_B}{\beta_{DC}} + I_C R_C = V_{CC} - V_{BE}$$

Then you can solve for I_C as follows:

$$I_C\left(R_C + \frac{R_B}{\beta_{DC}}\right) = V_{CC} - V_{BE}$$

$$\mathbf{I_C = \frac{V_{CC} - V_{BE}}{R_C + R_B/\beta_{DC}}}$$ **Equation 5–13**

Since the emitter is ground, $V_{CE} = V_C$.

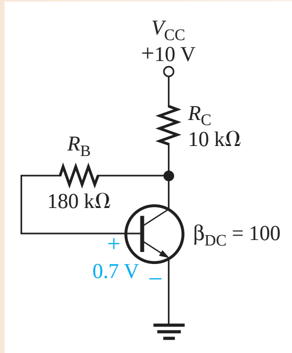
$$\mathbf{V_{CE} = V_{CC} - I_C R_C}$$ **Equation 5–14**

Q-Point Stability Over Temperature Equation 5–13 shows that the collector current is dependent to some extent on β_{DC} and V_{BE}. This dependency, of course, can be minimized by making $R_C \gg R_B/\beta_{DC}$ and $V_{CC} \gg V_{BE}$. An important feature of collector-feedback bias is that it essentially eliminates the β_{DC} and V_{BE} dependency even if the stated conditions are met.

As you have learned, β_{DC} varies directly with temperature, and V_{BE} varies inversely with temperature. As the temperature goes up in a collector-feedback circuit, β_{DC} goes up and V_{BE} goes down. The increase in β_{DC} acts to increase I_C. The decrease in V_{BE} acts to increase I_B which, in turn also acts to increase I_C. As I_C tries to increase, the voltage drop across R_C also tries to increase. This tends to reduce the collector voltage and therefore the voltage across R_B, thus reducing I_B and offsetting the attempted increase in I_C and the attempted decrease in V_C. The result is that the collector-feedback circuit maintains a relatively stable Q-point. The reverse action occurs when the temperature decreases.

EXAMPLE 5–10 Calculate the Q-point values (I_C and V_{CE}) for the circuit in Figure 5–23.

▶ **FIGURE 5–23**



Solution Using Equation 5–13, the collector current is

$$I_C = \frac{V_{CC} - V_{BE}}{R_C + R_B/\beta_{DC}} = \frac{10\text{ V} - 0.7\text{ V}}{10\text{ k}\Omega + 180\text{ k}\Omega/100} = \mathbf{788\ \mu A}$$

Using Equation 5–14, the collector-to-emitter voltage is

$$V_{CE} = V_{CC} - I_C R_C = 10\text{ V} - (788\ \mu\text{A})(10\text{ k}\Omega) = \mathbf{2.12\ V}$$

Related Problem Calculate the Q-point values in Figure 5–23 for $\beta_{DC} = 200$ and determine the percent change in the Q-point from $\beta_{DC} = 100$ to $\beta_{DC} = 200$.

Open the Multisim file E05-10 in the Examples folder on the companion website. Measure I_C and V_{CE}. Compare with the calculated values.

SECTION 5–3 CHECKUP

1. Why is emitter bias more stable than base bias?
2. What is the main disadvantage of emitter bias?
3. Explain how an increase in β_{DC} causes a reduction in base current in a collector-feedback circuit.
4. What is the main disadvantage of the base bias method?
5. Explain why the base bias Q-point changes with temperature.
6. How does emitter-feedback bias improve on base bias?

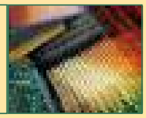
5–4 TROUBLESHOOTING

In a biased transistor circuit, the transistor can fail or a resistor in the bias circuit can fail. We will examine several possibilities in this section using the voltage-divider bias arrangement. Many circuit failures result from open resistors, internally open transistor leads and junctions, or shorted junctions. Often, these failures can produce an apparent cutoff or saturation condition when voltage is measured at the collector.

After completing this section, you should be able to

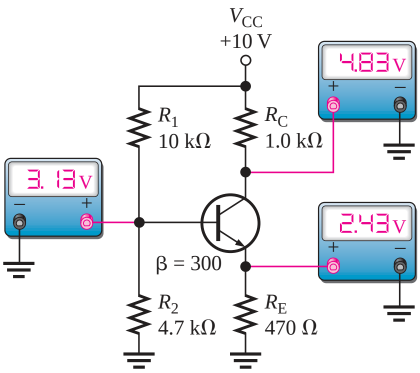
- **Troubleshoot faults in transistor bias circuits**
- Troubleshoot a voltage-divider biased transistor circuit
  - ◆ Troubleshoot the circuit for several common faults ◆ Use voltage measurement to isolate a fault

Chapter 18: Basic Programming Concepts for Automated Testing
Selected sections from Chapter 18 may be introduced as part of this troubleshooting coverage or, optionally, the entire Chapter 18 may be covered later or not at all.



Troubleshooting a Voltage-Divider Biased Transistor

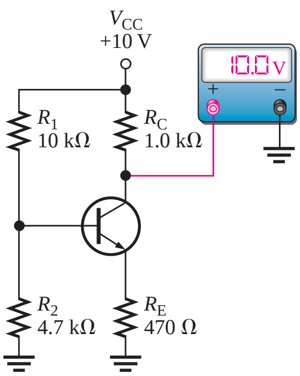
An example of a transistor with voltage-divider bias is shown in Figure 5–24. For the specific component values shown, you should get the voltage readings approximately as indicated when the circuit is operating properly.



◀ **FIGURE 5–24**

A voltage-divider biased transistor with correct voltages.

For this type of bias circuit, a particular group of faults will cause the transistor collector to be at V_{CC} when measured with respect to ground. Five faults are indicated for the circuit in Figure 5–25(a). The collector voltage is equal to 10 V with respect to ground for each of the faults as indicated in the table in part (b). Also, for each of the faults, the base voltage and the emitter voltage with respect to ground are given.



(a) Faulty circuit

FAULT	DESCRIPTION	V_C	V_E	V_B
1	R_1 open	10 V	0 V	0 V
2	R_E open	10 V	2.50 V	3.20 V
3	Base internally open	10 V	0 V	3.20 V
4	Emitter internally open	10 V	0 V	3.20 V
5	Collector internally open	10 V	0.41 V	1.11 V

(b) Possible faults for circuit in part (a)

▲ **FIGURE 5–25**

Faults for which $V_C = V_{CC}$.

Fault 1: Resistor R_1 Open This fault removes the bias voltage from the base, thus connecting the base to ground through R_2 and forcing the transistor into cutoff because $V_B = 0$ V and $I_B = 0$ A. The transistor is nonconducting so there is no I_C and, therefore, no voltage drop across R_C. This makes the collector voltage equal to V_{CC} (10 V). Since there is no base current or collector current, there is also no emitter current and $V_E = 0$ V.

Fault 2: Resistor R_E Open This fault prevents base current, emitter current, and collector current except for a very small I_{CBO} that can be neglected. Since $I_C = 0$ A, there is no voltage drop across R_C and, therefore, $V_C = V_{CC} = 10$ V. The voltage divider produces a voltage at the base with respect to ground as follows:

$$V_B = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\frac{4.7\text{ k}\Omega}{14.7\text{ k}\Omega}\right)10\text{ V} = 3.20\text{ V}$$

When a voltmeter is connected to the emitter, it provides a current path through its high internal impedance, resulting in a forward-biased base-emitter junction. Therefore, the emitter voltage is $V_E = V_B - V_{BE}$. The amount of the forward voltage drop across the BE junction depends on the current. $V_{BE} = 0.7$ V is assumed for purposes of illustration, but it may be much less. The result is an emitter voltage as follows:

$$V_E = V_B - V_{BE} = 3.2\text{ V} - 0.7\text{ V} = 2.5\text{ V}$$

Fault 3: Base Internally Open An internal transistor fault is more likely to happen than an open resistor. Again, the transistor is nonconducting so $I_C = 0$ A and $V_C = V_{CC} = 10$ V. Just as for the case of the open R_E, the voltage divider produces 3.2 V at the external base connection. The voltage at the external emitter connection is 0 V because there is no emitter current through R_E and, thus, no voltage drop.

Fault 4: Emitter Internally Open Again, the transistor is nonconducting, so $I_C = 0$ A and $V_C = V_{CC} = 10$ V. Just as for the case of the open R_E and the internally open base, the voltage divider produces 3.2 V at the base. The voltage at the external emitter lead is 0 V because that point is open and connected to ground through R_E. Notice that Faults 3 and 4 produce identical symptoms.

Fault 5: Collector Internally Open Since there is an internal open in the transistor collector, there is no I_C and, therefore, $V_C = V_{CC} = 10$ V. In this situation, the voltage divider is loaded by R_E through the forward-biased BE junction, as shown by the approximate equivalent circuit in Figure 5–26. The base voltage and emitter voltage are determined as follows:

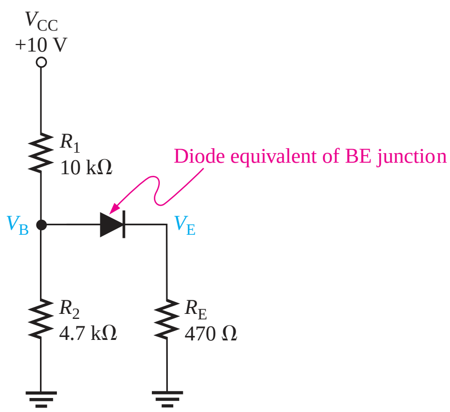
$$V_B \cong \left(\frac{R_2 \| R_E}{R_1 + R_2 \| R_E}\right)V_{CC} + 0.7\text{ V}$$

$$= \left(\frac{427\ \Omega}{10.427\text{ k}\Omega}\right)10\text{ V} + 0.7\text{ V} = 0.41\text{ V} + 0.7\text{ V} = 1.11\text{ V}$$

$$V_E = V_B - V_{BE} = 1.11\text{ V} - 0.7\text{ V} = 0.41\text{ V}$$

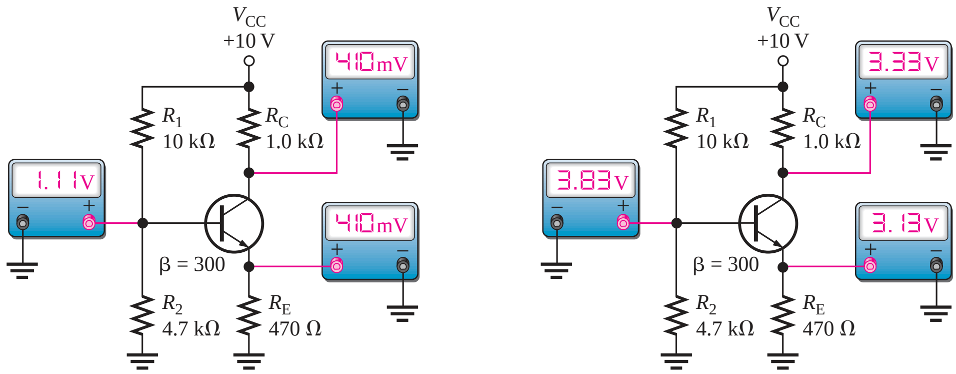
▶ **FIGURE 5–26**

Equivalent bias circuit for an internally open collector.



There are two possible additional faults for which the transistor is conducting or appears to be conducting, based on the collector voltage measurement. These are indicated in Figure 5–27.

Fault 6: Resistor R_C Open For this fault, which is illustrated in Figure 5–27(a), the collector voltage may lead you to think that the transistor is in saturation, but actually it is



(a) R_C open (b) R_2 open

FIGURE 5–27

Faults for which the transistor is conducting or appears to be conducting.

nonconducting. Obviously, if R_C is open, there can be no collector current. In this situation, the equivalent bias circuit is the same as for Fault 5, as illustrated in Figure 5–26. Therefore, $V_B = 1.11$ V and since the BE junction is forward-biased,

$$V_E = V_B - V_{BE} = 1.11\text{ V} - 0.7\text{ V} = 0.41\text{ V}$$

When a voltmeter is connected to the collector to measure V_C, a current path is provided through the internal impedance of the meter and the BC junction is forward-biased by V_B. Therefore,

$$V_C = V_B - V_{BC} = 1.11\text{ V} - 0.7\text{ V} = 0.41\text{ V}$$

Again the forward drops across the internal transistor junctions depend on the current. We are using 0.7 V for illustration, but the forward drops may be much less.

Fault 7: Resistor R_2 Open When R_2 opens as shown in Figure 5–27(b), the base voltage and base current increase from their normal values because the voltage divider is now formed by R_1 and $R_{IN(BASE)}$. In this case, the base voltage is determined by the emitter voltage ($V_B = V_E + V_{BE}$).

First, verify whether the transistor is in saturation or not. The collector saturation current and the base current required to produce saturation are determined as follows (assuming $V_{CE(sat)} = 0.2$ V):

$$I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C + R_E} = \frac{9.8\text{ V}}{1.47\text{ k}\Omega} = 6.67\text{ mA}$$

$$I_{B(sat)} = \frac{I_{C(sat)}}{\beta_{DC}} = \frac{6.67\text{ mA}}{300} = 22.2\ \mu\text{A}$$

Assuming the transistor is saturated, the maximum base current is determined.

$$I_{E(sat)} \cong 6.67\text{ mA}$$

$$V_E = I_{E(sat)}R_E = 3.13\text{ V}$$

$$V_B = V_E + V_{BE} = 3.83\text{ V}$$

$$R_{IN(BASE)} = \frac{B_{DC}V_B}{I_E} = \frac{(300)(3.83\text{ V})}{6.67\text{ mA}} = 172\text{ k}\Omega$$

$$I_B = \frac{V_{CC}}{R_1 + R_{IN(BASE)}} = \frac{10\text{ V}}{182\text{ k}\Omega} = 54.9\text{ mA}$$

Since this amount of base current is more than enough to produce saturation, the transistor is definitely saturated. Therefore, V_E, V_B, and V_C are as follows:

$$V_E = 3.13\text{ V}$$

$$V_B = 3.83\text{ V}$$

$$V_C = V_{CC} - I_{C(sat)}R_C = 10\text{ V} - (6.67\text{ mA})(1.0\text{ k}\Omega) = 3.33\text{ V}$$

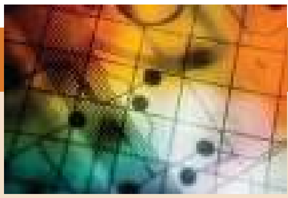
Multisim Troubleshooting Exercises

These file circuits are in the Troubleshooting Exercises folder on the companion website. Open each file and determine if the circuit is working properly. If it is not working properly, determine the fault.

1. Multisim file TSE05-01
2. Multisim file TSE05-02
3. Multisim file TSE05-03
4. Multisim file TSE05-04
5. Multisim file TSE05-05

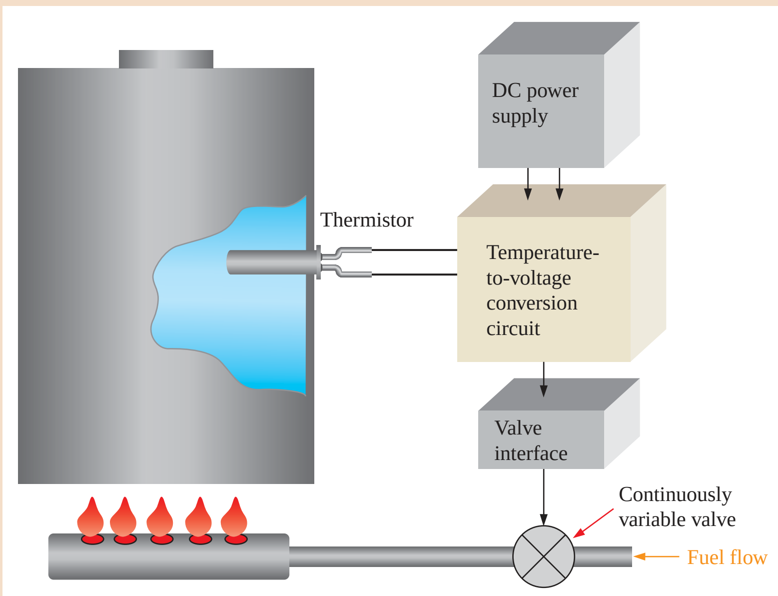
SECTION 5–4 CHECKUP

1. How do you determine when a transistor is saturated? When a transistor is in cutoff?
2. In a voltage-divider biased *npn* transistor circuit, you measure V_{CC} at the collector and an emitter voltage 0.7 V less than the base voltage. Is the transistor functioning in cutoff, or is R_E open?
3. What symptoms does an open R_C produce?



Application Activity: *Temperature to Voltage Conversion*

The focus of this Application Activity is a temperature-sensing circuit that converts the temperature of a liquid to a proportional voltage for the purpose of maintaining the temperature of the liquid within a specified range. Figure 5–28 illustrates the temperature-control system. The temperature sensor is a **thermistor**, which is a device whose resistance changes with temperature. The thermistor is connected to a transistor circuit that is biased for linear operation. The output voltage of the circuit is proportional to the thermistor resistance and thus to the temperature of the liquid in the tank. The output voltage goes to an interface circuit that



▶ **FIGURE 5–28**

Temperature-control system.

controls the valve to control the flow of fuel to the burner based on the voltage. If the temperature of the liquid is below a set value, the fuel is increased and if it is above that value, the fuel is decreased. The temperature is to be maintained at 70°C ± 5°C.

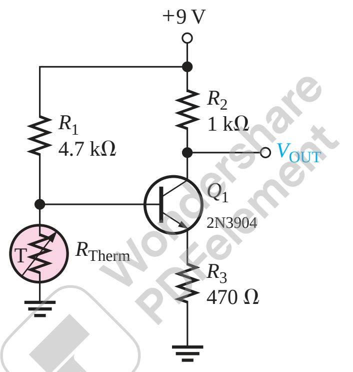
Designing the Circuit

Circuit Configuration A voltage-divider biased linear amplifier is used for the temperature-to-voltage conversion. The thermistor is used as one of the resistors in the voltage-divider bias. This thermistor has a positive temperature coefficient so, if the temperature increases, the resistance of the thermistor increases and if the temperature decreases, the resistance decreases. The base voltage changes proportionally to the change in thermistor resistance. The output voltage is inversely proportional to the base voltage, so as the temperature goes up, the output voltage decreases and reduces the fuel flow to the burner. As the temperature goes down, the output voltage increases and allows more fuel to the burner.

Components As shown in Figure 5–29(a), the circuit is implemented with a 2N3904 transistor, three resistors and a thermistor with the values shown, and a +9 V dc source. The thermistor has the temperature characteristic shown in part (b).

▶ **FIGURE 5–29**

Temperature-to-voltage conversion circuit.



(a) Circuit

TEMPERATURE, °C	THERMISTOR RESISTANCE, kΩ
60	1.256
65	1.481
70	1.753
75	2.084
80	2.490

(b) Temperature characteristic of the thermistor for the specified range

1. Plot a graph of the thermistor temperature characteristic.
2. Refer to Figure 5–29 and calculate the emitter and collector currents for each temperature shown.
3. Calculate the output voltage for each temperature shown in Figure 5–29.

Simulation

The temperature-to-voltage conversion circuit is simulated to determine how the output voltage changes with temperature, as shown in Figure 5–30. The thermistor is represented by a resistor with values corresponding to each specified temperature.

4. Compare your calculations for the output voltage with the simulated values.

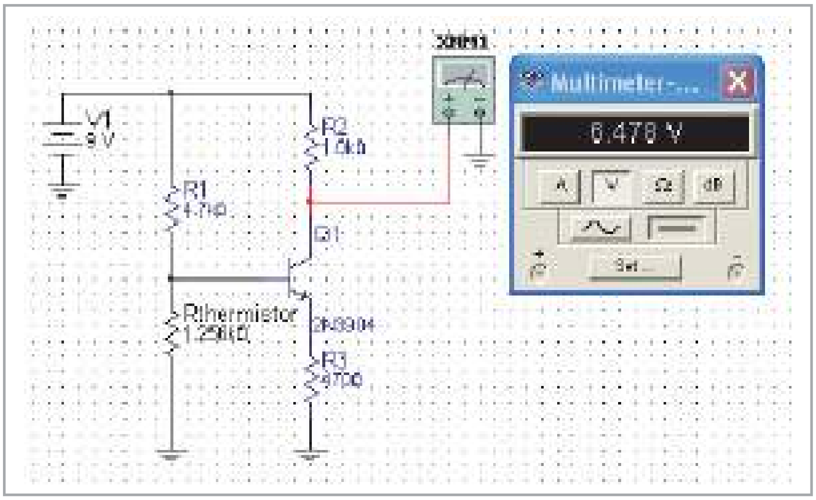
Simulate the circuit using your Multisim software. Observe the operation with the virtual multimeter.

Prototyping and Testing

Now that all the components have been selected, the prototype circuit is constructed and tested. After the circuit is successfully tested, it is ready to be finalized on a printed circuit board.

Lab Experiment

To build and test a similar circuit, go to Experiment 5 in your lab manual (*Laboratory Exercises for Electronic Devices* by David Buchla and Steven Wetterling).



(a) Circuit output voltage at 60° C

R_{therm} = 1.481 kΩ R_{therm} = 1.753 kΩ R_{therm} = 2.084 kΩ R_{therm} = 2.490 kΩ

(b) Circuit output voltages at 65°, 70°, 75°, and 80°

▲ **FIGURE 5–30**

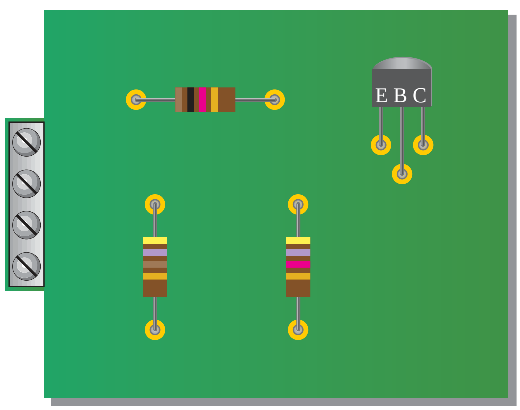
Operation of the temperature-to-voltage conversion circuit over temperature.

The Printed Circuit Board

A partially completed printed circuit board is shown in Figure 5–31. Indicate how you would add conductive traces to complete the circuit and show the input/output terminal functions.

▶ **FIGURE 5–31**

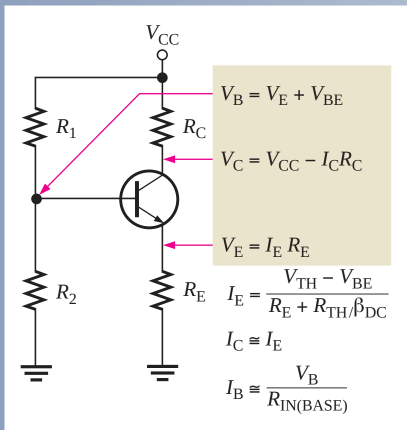
Partially complete temperature conversion circuit PC board.



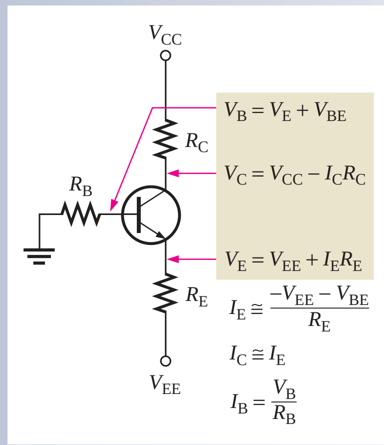
SUMMARY OF TRANSISTOR BIAS CIRCUITS

npn transistors are shown. Supply voltage polarities are reversed for *pnp* transistors.

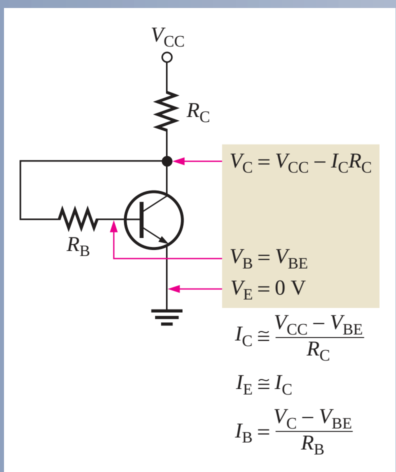
VOLTAGE-DIVIDER BIAS



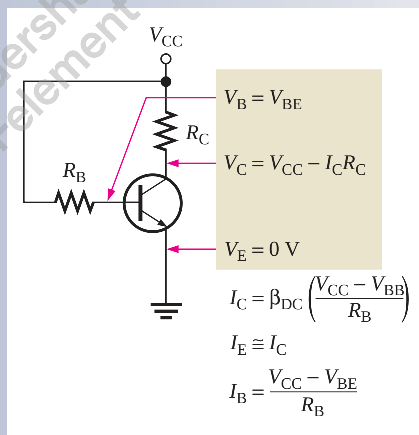
EMITTER BIAS



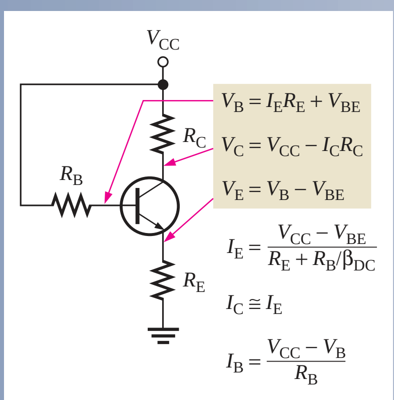
COLLECTOR-FEEDBACK BIAS



BASE BIAS



EMITTER-FEEDBACK BIAS



SUMMARY

Section 5–1

- The purpose of biasing a circuit is to establish a proper stable dc operating point (Q-point).
- The Q-point of a circuit is defined by specific values for I_C and V_{CE}. These values are called the coordinates of the Q-point.
- A dc load line passes through the Q-point on a transistor's collector curves intersecting the vertical axis at approximately $I_{C(sat)}$ and the horizontal axis at $V_{CE(off)}$.
- The linear (active) operating region of a transistor lies along the load line below saturation and above cutoff.

Section 5–2

- Loading effects are neglected for a stiff voltage divider.
- The dc input resistance at the base of a BJT is approximately $\beta_{DC}R_E$.
- Voltage-divider bias provides good Q-point stability with a single-polarity supply voltage. It is the most common bias circuit.

Section 5–3

- Emitter bias generally provides good Q-point stability but requires both positive and negative supply voltages.
- The base bias circuit arrangement has poor stability because its Q-point varies widely with β_{DC}.
- Emitter-feedback bias combines base bias with the addition of an emitter resistor.
- Collector-feedback bias provides good stability using negative feedback from collector to base.

KEY TERMS

Key terms and other bold terms in the chapter are defined in the end-of-book glossary.

DC load line A straight line plot of I_C and V_{CE} for a transistor circuit.

Feedback The process of returning a portion of a circuit's output back to the input in such a way as to oppose or aid a change in the output.

Linear region The region of operation along the load line between saturation and cutoff.

Q-point The dc operating (bias) point of an amplifier specified by voltage and current values.

Stiff voltage divider A voltage divider for which loading effects can be neglected.

KEY FORMULAS

Voltage-Divider Bias

5–1 $$V_B \cong \left(\frac{R_2}{R_1 + R_2}\right)V_{CC}$$ for a stiff voltage divider

5–2 $$V_E = V_B - V_{BE}$$

5–3 $$I_C \cong I_E = \frac{V_E}{R_E}$$

5–4 $$V_C = V_{CC} - I_C R_C$$

5–5 $$R_{IN(BASE)} = \frac{\beta_{DC} V_B}{I_E}$$

5–6 $$I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}}$$

5–7 $$I_E = \frac{-V_{TH} + V_{BE}}{R_E + R_{TH}/\beta_{DC}}$$

5–8 $$I_E = \frac{V_{TH} + V_{BE} - V_{EE}}{R_E + R_{TH}/\beta_{DC}}$$

Emitter Bias

5–9 $$I_E = \frac{-V_{EE} - V_{BE}}{R_E + R_B/\beta_{DC}}$$

Base Bias

5–10 $$V_{CE} = V_{CC} - I_C R_C$$

5–11 $$I_C = \beta_{DC}\left(\frac{V_{CC} - V_{BE}}{R_B}\right)$$

Emitter-Feedback Bias

5–12 $$I_E = \frac{V_{CC} - V_{BE}}{R_E + R_B/\beta_{DC}}$$

Collector-Feedback Bias

5–13 $$I_C = \frac{V_{CC} - V_{BE}}{R_C + R_B/\beta_{DC}}$$

5–14 $$V_{CE} = V_{CC} - I_C R_C$$

TRUE/FALSE QUIZ

Answers can be found at www.pearsonhighered.com/floyd.

1. DC bias establishes the dc operating point for an amplifier.
2. Q-point is the quadratic point in a bias circuit.
3. The dc load line intersects the horizontal axis of a transistor characteristic curve at $V_{CE} = V_{CC}$.
4. The dc load line intersects the vertical axis of a transistor characteristic curve at $I_C = 0$.
5. The linear region of a transistor's operation lies between saturation and cutoff.
6. Voltage-divider bias is rarely used.
7. Input resistance at the base of the transistor can affect voltage-divider bias.
8. Stiff voltage-divider bias is essentially independent of base loading.
9. Emitter bias uses one dc supply voltage.
10. Negative feedback is employed in collector-feedback bias.
11. Base bias is less stable than voltage-divider bias.
12. A *pnp* transistor requires bias voltage polarities opposite to an *npn* transistor.

CIRCUIT-ACTION QUIZ

Answers can be found at www.pearsonhighered.com/floyd.

1. If V_{BB} in Figure 5–7 is increased, the Q-point value of collector current will
   (a) increase **(b)** decrease **(c)** not change
2. If V_{BB} in Figure 5–7 is increased, the Q-point value of V_{CE} will
   (a) increase **(b)** decrease **(c)** not change
3. If the value of R_2 in Figure 5–10 is reduced, the base voltage will
   (a) increase **(b)** decrease **(c)** not change
4. If the value of R_1 in Figure 5–10 is increased, the emitter current will
   (a) increase **(b)** decrease **(c)** not change
5. If R_E in Figure 5–15 is decreased, the collector current will
   (a) increase **(b)** decrease **(c)** not change
6. If R_B in Figure 5–18 is reduced, the base-to-emitter voltage will
   (a) increase **(b)** decrease **(c)** not change
7. If V_{CC} in Figure 5–20 is increased, the base-to-emitter voltage will
   (a) increase **(b)** decrease **(c)** not change
8. If R_1 in Figure 5–24 opens, the collector voltage will
   (a) increase **(b)** decrease **(c)** not change
9. If R_2 in Figure 5–24 opens, the collector voltage will
   (a) increase **(b)** decrease **(c)** not change
10. If R_2 in Figure 5–24 is increased, the emitter current will
    (a) increase **(b)** decrease **(c)** not change

SELF-TEST

Answers can be found at www.pearsonhighered.com/floyd.

Section 5–1

1. The maximum value of collector current in a biased transistor is

(a) $\beta_{DC}I_B$ **(b)** $I_{C(sat)}$ **(c)** greater than I_E **(d)** $I_E - I_B$

2. Ideally, a dc load line is a straight line drawn on the collector characteristic curves between

(a) the Q-point and cutoff **(b)** the Q-point and saturation

(c) $V_{CE(cutoff)}$ and $I_{C(sat)}$ **(d)** $I_B = 0$ and $I_B = I_C/\beta_{DC}$

3. If a sinusoidal voltage is applied to the base of a biased *npn* transistor and the resulting sinusoidal collector voltage is clipped near zero volts, the transistor is

(a) being driven into saturation **(b)** being driven into cutoff

(c) operating nonlinearly **(d)** answers (a) and (c)

(e) answers (b) and (c)

Section 5–2

4. The input resistance at the base of a biased transistor depends mainly on

(a) β_{DC} **(b)** R_B **(c)** R_E **(d)** β_{DC} and R_E

5. In a voltage-divider biased transistor circuit such as in Figure 5–13, $R_{IN(BASE)}$ can generally be neglected in calculations when

(a) $R_{IN(BASE)} > R_2$ **(b)** $R_2 > 10R_{IN(BASE)}$ **(c)** $R_{IN(BASE)} > 10R_2$ **(d)** $R_1 \ll R_2$

6. In a certain voltage-divider biased *npn* transistor, V_B is 2.95 V. The dc emitter voltage is approximately

(a) 2.25 V **(b)** 2.95 V **(c)** 3.65 V **(d)** 0.7 V

7. Voltage-divider bias

(a) cannot be independent of β_{DC} **(b)** can be essentially independent of β_{DC}

(c) is not widely used **(d)** requires fewer components than all the other methods

Section 5–3

8. Emitter bias is

(a) essentially independent of β_{DC} **(b)** very dependent on β_{DC}

(c) provides a stable bias point **(d)** answers (a) and (c)

9. In an emitter bias circuit, $R_E = 2.7\ k\Omega$ and $V_{EE} = 15$ V. The emitter current

(a) is 5.3 mA **(b)** is 2.7 mA

(c) is 180 mA **(d)** cannot be determined

10. The disadvantage of base bias is that

(a) it is very complex **(b)** it produces low gain

(c) it is too beta dependent **(d)** it produces high leakage current

11. Collector-feedback bias is

(a) based on the principle of positive feedback **(b)** based on beta multiplication

(c) based on the principle of negative feedback **(d)** not very stable

Section 5–4

12. In a voltage-divider biased *npn* transistor, if the upper voltage-divider resistor (the one connected to V_{CC}) opens,

(a) the transistor goes into cutoff **(b)** the transistor goes into saturation

(c) the transistor burns out **(d)** the supply voltage is too high

13. In a voltage-divider biased *npn* transistor, if the lower voltage-divider resistor (the one connected to ground) opens,

(a) the transistor is not affected **(b)** the transistor may be driven into cutoff

(c) the transistor may be driven into saturation **(d)** the collector current will decrease

14. In a voltage-divider biased *pnp* transistor, there is no base current, but the base voltage is approximately correct. The most likely problem(s) is

(a) a bias resistor is open **(b)** the collector resistor is open

(c) the base-emitter junction is open **(d)** the emitter resistor is open

(e) answers (a) and (c) **(f)** answers (c) and (d)

15. If R_1 in Figure 5–25 is open, the base voltage is

(a) +10 V **(b)** 0 V **(c)** 3.13 V **(d)** 0.7 V

16. If R_1 is open, the collector current in Figure 5–25 is

(a) 5.17 mA **(b)** 10 mA **(c)** 4.83 mA **(d)** 0 mA

PROBLEMS

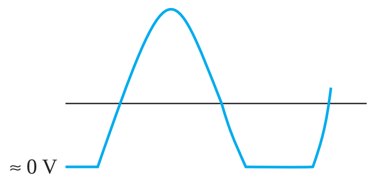
Answers to all odd-numbered problems are at the end of the book.

BASIC PROBLEMS

Section 5–1 The DC Operating Point

1. The output (collector voltage) of a biased transistor amplifier is shown in Figure 5–32. Is the transistor biased too close to cutoff or too close to saturation?

▶ FIGURE 5–32



2. What is the Q-point for a biased transistor as in Figure 5–2 with $I_B = 150\ \mu A$, $\beta_{DC} = 75$, $V_{CC} = 18$ V, and $R_C = 1.0\ k\Omega$?

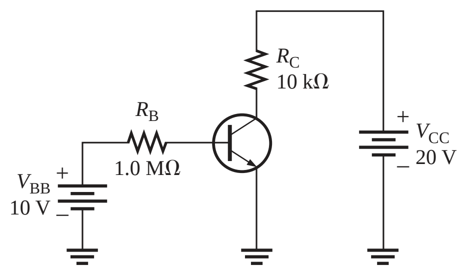
3. What is the saturation value of collector current in Problem 2?

4. What is the cutoff value of V_{CE} in Problem 2?

5. Determine the intercept points of the dc load line on the vertical and horizontal axes of the collector-characteristic curves for the circuit in Figure 5–33.

▶ FIGURE 5–33

Multisim file circuits are identified with a logo and are in the Problems folder on the companion website. Filenames correspond to figure numbers (e.g., F05-33).

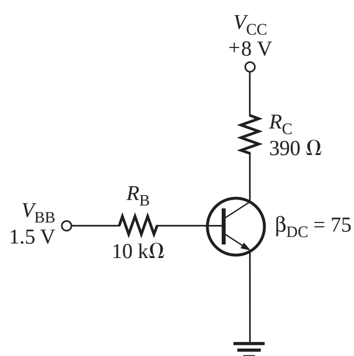


6. Assume that you wish to bias the transistor in Figure 5–33 with $I_B = 20\ \mu A$. To what voltage must you change the V_{BB} supply? What are I_C and V_{CE} at the Q-point, given that $\beta_{DC} = 50$?

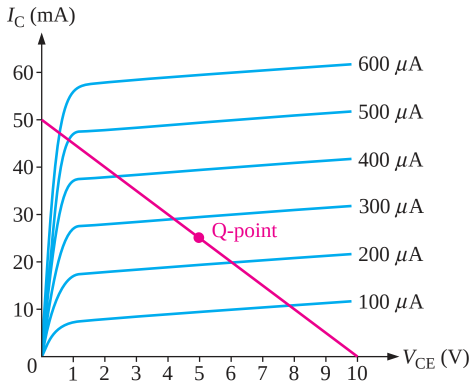
7. Design a biased-transistor circuit using $V_{BB} = V_{CC} = 10$ V for a Q-point of $I_C = 5$ mA and $V_{CE} = 4$ V. Assume $\beta_{DC} = 100$. The design involves finding R_B, R_C, and the *minimum* power rating of the transistor. (The actual power rating should be greater.) Sketch the circuit.

8. Determine whether the transistor in Figure 5–34 is biased in cutoff, saturation, or the linear region. Remember that $I_C = \beta_{DC} I_B$ is valid only in the linear region.

▶ FIGURE 5–34



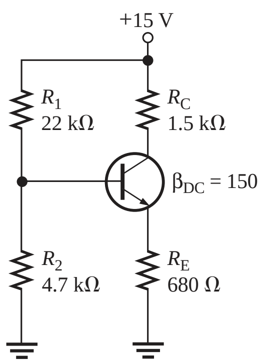
▶ FIGURE 5–35



9. From the collector characteristic curves and the dc load line in Figure 5–35, determine the following:
   (a) Collector saturation current
   (b) V_{CE} at cutoff
   (c) Q-point values of I_B, I_C, and V_{CE}

10. From Figure 5–35 determine the following:
   (a) Maximum collector current for linear operation
   (b) Base current at the maximum collector current
   (c) V_{CE} at maximum collector current

Section 5–2 Voltage-Divider Bias



▲ FIGURE 5–36

11. What is the minimum value of β_{DC} in Figure 5–36 that makes $R_{IN(BASE)} \geqq 10R_2$?

12. The bias resistor R_2 in Figure 5–36 is replaced by a 15 kΩ potentiometer. What minimum resistance setting causes saturation?

13. If the potentiometer described in Problem 12 is set at 2 kΩ, what are the values for I_C and V_{CE}?

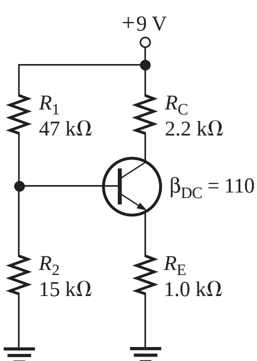
14. Determine all transistor terminal voltages with respect to ground in Figure 5–37.

15. Show the connections required to replace the transistor in Figure 5–37 with a *pnp* device.

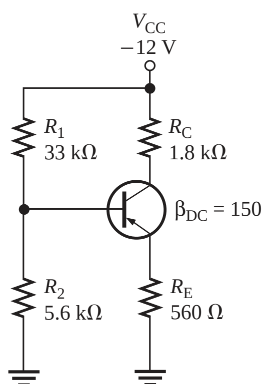
16. **(a)** Determine V_B in Figure 5–38.
   (b) How is V_B affected if the transistor is replaced by one with a β_{DC} of 50?

17. Determine the following in Figure 5–38:
   (a) Q-point values
   (b) The minimum power rating of the transistor

18. Determine I_1, I_2, and I_B in Figure 5–38.



▲ FIGURE 5–37



▲ FIGURE 5–38

Section 5–3 Other Bias Methods

19. Analyze the circuit in Figure 5–39 to determine the correct voltages at the transistor terminals with respect to ground. Assume $\beta_{DC} = 100$.

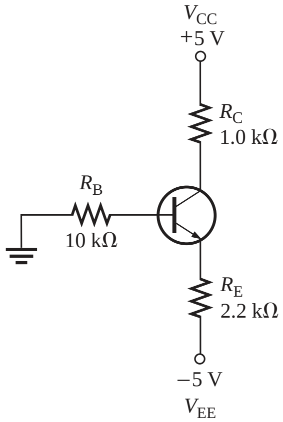
20. To what value can R_E in Figure 5–39 be reduced without the transistor going into saturation?

21. Taking V_{BE} into account in Figure 5–39, how much will I_E change with a temperature increase from 25°C to 100°C? The V_{BE} is 0.7 V at 25°C and decreases 2.5 mV per degree Celsius. Neglect any change in β_{DC}.

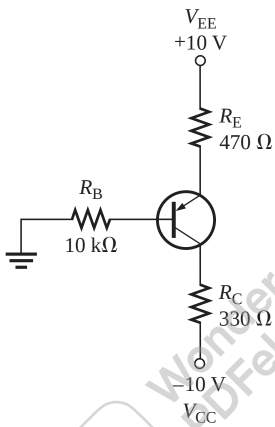
22. When can the effect of a change in β_{DC} be neglected in the emitter bias circuit?

23. Determine I_C and V_{CE} in the *pnp* emitter bias circuit of Figure 5–40. Assume $\beta_{DC} = 100$.

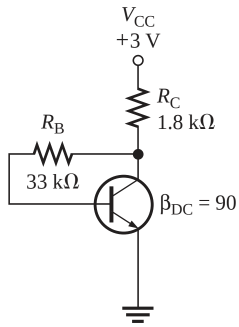
24. Determine V_B, V_C, and I_C in Figure 5–41.



▲ FIGURE 5–39



▲ FIGURE 5–40



▲ FIGURE 5–41

25. What value of R_C can be used to decrease I_C in Problem 24 by 25 percent?

26. What is the minimum power rating for the transistor in Problem 25?

27. A collector-feedback circuit uses an *npn* transistor with $V_{CC} = 12$ V, $R_C = 1.2$ kΩ, and $R_B = 47$ kΩ. Determine the collector current and the collector voltage if $\beta_{DC} = 200$.

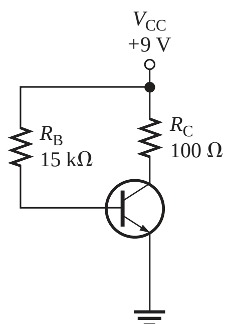
28. Determine I_B, I_C, and V_{CE} for a base-biased transistor circuit with the following values: $\beta_{DC} = 90$, $V_{CC} = 12$ V, $R_B = 22$ kΩ, and $R_C = 100$ Ω.

29. If β_{DC} in Problem 28 doubles over temperature, what are the Q-point values?

30. You have two base bias circuits connected for testing. They are identical except that one is biased with a separate V_{BB} source and the other is biased with the base resistor connected to V_{CC}. Ammeters are connected to measure collector current in each circuit. You vary the V_{CC} supply voltage and observe that the collector current varies in one circuit, but not in the other. In which circuit does the collector current change? Explain your observation.

31. The datasheet for a particular transistor specifies a minimum β_{DC} of 50 and a maximum β_{DC} of 125. What range of Q-point values can be expected if an attempt is made to mass-produce the circuit in Figure 5–42? Is this range acceptable if the Q-point must remain in the transistor's linear region?

32. The base bias circuit in Figure 5–42 is subjected to a temperature variation from 0°C to 70°C. The β_{DC} decreases by 50 percent at 0°C and increases by 75 percent at 70°C from its nominal value of 110 at 25°C. What are the changes in I_C and V_{CE} over the temperature range of 0°C to 70°C?

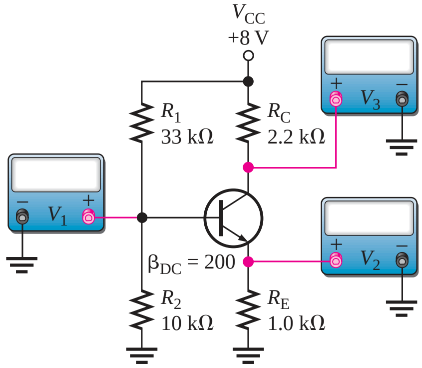


▲ FIGURE 5–42

Section 5–4 Troubleshooting

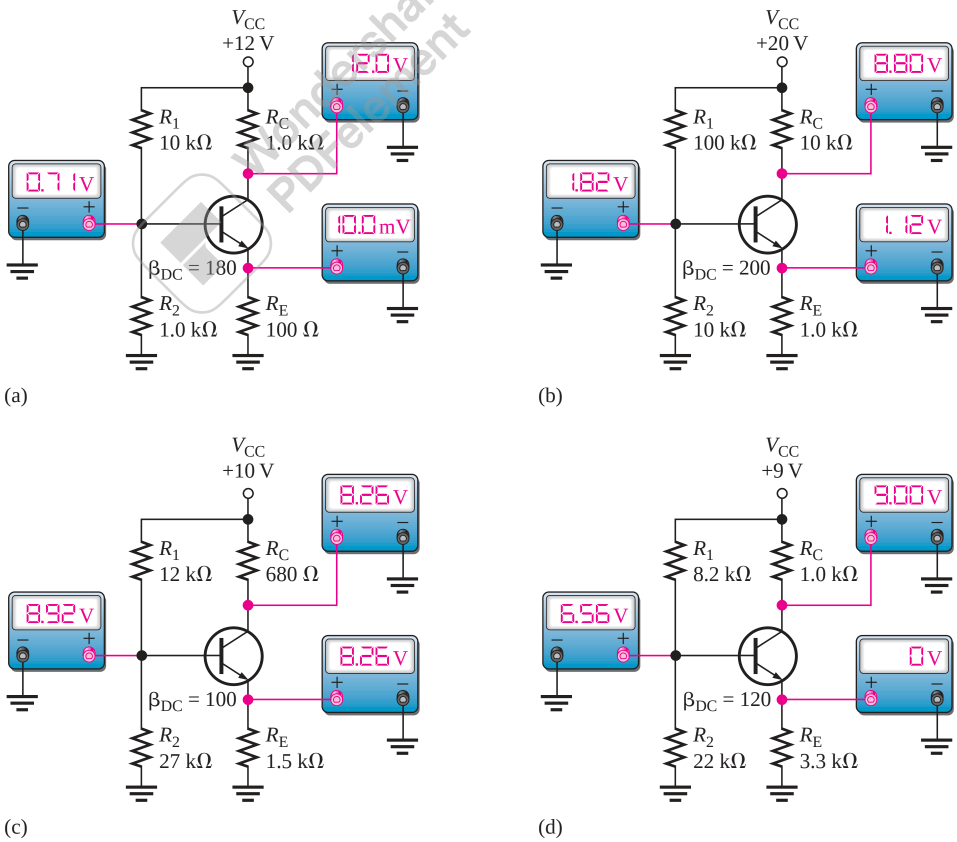
33. Determine the meter readings in Figure 5–43 if R_1 is open.

▶ FIGURE 5–43



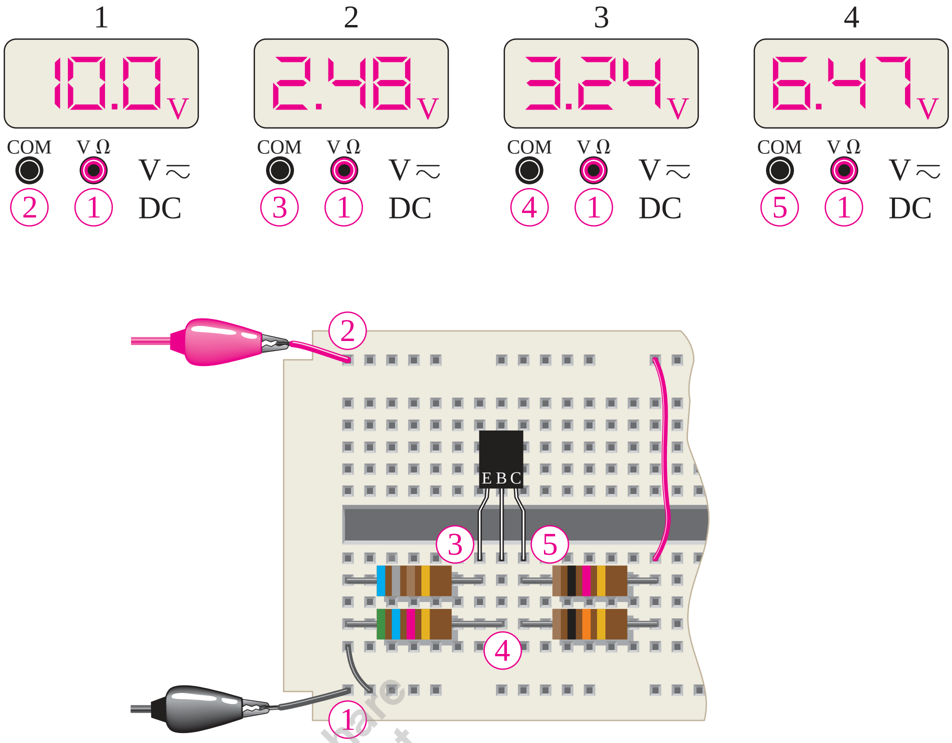
34. Assume the emitter becomes shorted to ground in Figure 5–43 by a solder splash or stray wire clipping. What do the meters read? When you correct the problem, what do the meters read?

35. Determine the most probable failures, if any, in each circuit of Figure 5–44, based on the indicated measurements.



▲ FIGURE 5–44

36. Determine if the DMM readings 2 through 4 in the breadboard circuit of Figure 5–45 are correct. If they are not, isolate the problem(s). The transistor is a *pnp* device with a specified dc beta range of 35 to 100.



▲ FIGURE 5–45

37. Determine each meter reading in Figure 5–45 for each of the following faults:

(a) the 680 Ω resistor open
(b) the 5.6 kΩ resistor open
(c) the 10 kΩ resistor open
(d) the 1.0 kΩ resistor open
(e) a short from emitter to ground
(f) an open base-emitter junction

APPLICATION ACTIVITY PROBLEMS

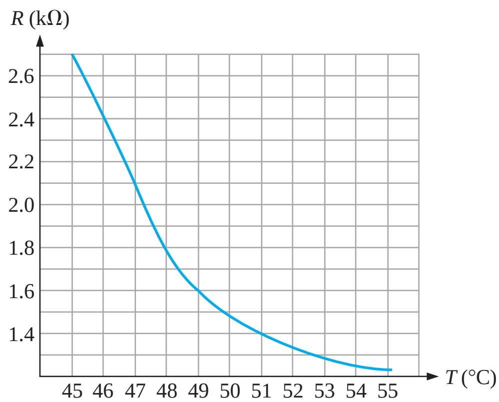
38. Determine V_B, V_E, and V_C in the temperature-to-voltage conversion circuit in Figure 5–29(a) if R_1 fails open.

39. What faults will cause the transistor in the temperature-to-voltage conversion circuit to go into cutoff?

40. A thermistor with the characteristic curve shown in Figure 5–46 is used in the circuit of Figure 5–29(a). Calculate the output voltage for temperatures of 45°C, 48°C, and 53°C. Assume a stiff voltage divider.

41. Explain how you would identify an open collector-base junction in the transistor in Figure 5–29(a).

► FIGURE 5–46

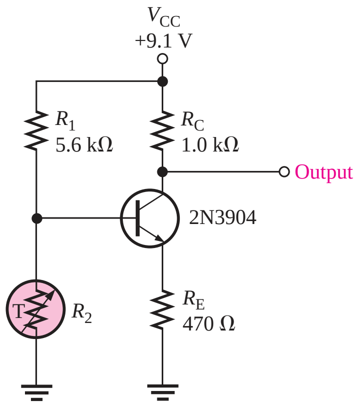


DATASHEET PROBLEMS

42. Analyze the temperature-to-voltage conversion circuit in Figure 5–47 at the temperature extremes indicated on the graph in Figure 5–46 for both minimum and maximum specified datasheet values of h_{FE}. Refer to the partial datasheet in Figure 5–48.

43. Verify that no maximum ratings are exceeded in the temperature-to-voltage conversion circuit in Figure 5–47. Refer to the partial datasheet in Figure 5–48.

▶ **FIGURE 5–47**



▶ **FIGURE 5–48**

Partial datasheet for the 2N3904 transistor. Copyright Fairchild Semiconductor Corporation. Used by permission.

Absolute Maximum Ratings* T_A = 25°C unless otherwise noted

Symbol	Parameter	Value	Units
V_{CEO}	Collector-Emitter Voltage	40	V
V_{CBO}	Collector-Base Voltage	60	V
V_{EBO}	Emitter-Base Voltage	6.0	V
I_C	Collector Current - Continuous	200	mA
T_J, T_{stg}	Operating and Storage Junction Temperature Range	-55 to +150	°C

*These ratings are limiting values above which the serviceability of any semiconductor device may be impaired.

NOTES:
1) These ratings are based on a maximum junction temperature of 150 degrees C.
2) These are steady state limits. The factory should be consulted on applications involving pulsed or low duty cycle operations.

ON CHARACTERISTICS*

h_{FE}	DC Current Gain	I_C = 0.1 mA, V_{CE} = 1.0 V I_C = 1.0 mA, V_{CE} = 1.0 V I_C = 10 mA, V_{CE} = 1.0 V I_C = 50 mA, V_{CE} = 1.0 V I_C = 100 mA, V_{CE} = 1.0 V	40 70 100 60 30	300	
$V_{CE(sat)}$	Collector-Emitter Saturation Voltage	I_C = 10 mA, I_B = 1.0 mA I_C = 50 mA, I_B = 5.0 mA		0.2 0.3	V V
$V_{BE(sat)}$	Base-Emitter Saturation Voltage	I_C = 10 mA, I_B = 1.0 mA I_C = 50 mA, I_B = 5.0 mA	0.65	0.85 0.95	V V

44. Refer to the partial datasheet in Figure 5–49.

(a) What is the maximum collector current for a 2N2222A?

(b) What is the maximum reverse base-emitter voltage for a 2N2218A?

45. Determine the maximum power dissipation for a 2N2222A at 100°C.

46. When you increase the collector current in a 2N2219A from 1 mA to 500 mA, how much does the minimum β_{DC} (h_{FE}) change?

ADVANCED PROBLEMS

47. Design a circuit using base bias that operates from a 15 V dc voltage and draws a maximum current from the dc source ($I_{CC(max)}$) of 10 mA. The Q-point values are to be I_C = 5 mA and V_{CE} = 5 V. The transistor is a 2N3904. Assume a midpoint value for β_{DC}.

Maximum Ratings

Rating	Symbol	2N2218 2N2219 2N2221 2N2222	2N2218A 2N2219A 2N2221A 2N2222A	2N5581 2N5582	Unit
Collector-Emitter voltage	V_{CEO}	30	40	40	V dc
Collector-Base voltage	V_{CBO}	60	75	75	V dc
Emitter-Base voltage	V_{EBO}	5.0	6.0	6.0	V dc
Collector current — continuous	I_C	800	800	800	mA dc
		2N2218,A 2N2219,A	**2N2221,A 2N2222,A**	**2N5581 2N5582**	
Total device dissipation @ $T_A = 25°C$ Derate above 25°C	P_D	0.8 4.57	0.5 2.28	0.6 3.33	Watt mW/°C
Total device dissipation @ $T_C = 25°C$ Derate above 25°C	P_D	3.0 17.1	1.2 6.85	2.0 11.43	Watt mW/°C
Operating and storage junction Temperature range	T_J, T_{stg}		−65 to +200		°C

Electrical Characteristics ($T_A = 25°C$ unless otherwise noted.)

Characteristic		Symbol	Min	Max	Unit
Off Characteristics					
Collector-Emitter breakdown voltage ($I_C = 10$ mA dc, $I_B = 0$)	Non-A Suffix A-Suffix, 2N5581, 2N5582	$V_{(BR)CEO}$	30 40	— —	V dc
Collector-Base breakdown voltage ($I_C = 10\ \mu$A dc, $I_E = 0$)	Non-A Suffix A-Suffix, 2N5581, 2N5582	$V_{(BR)CBO}$	60 75	— —	V dc
Emitter-Base breakdown voltage ($I_E = 10\ \mu$A dc, $I_C = 0$)	Non-A Suffix A-Suffix, 2N5581, 2N5582	$V_{(BR)EBO}$	5.0 6.0	— —	V dc
Collector cutoff current ($V_{CE} = 60$ V dc, $V_{EB(off)} = 3.0$ V dc	A-Suffix, 2N5581, 2N5582	I_{CEX}	—	10	nA dc
Collector cutoff current ($V_{CB} = 50$ V dc, $I_E = 0$) ($V_{CB} = 60$ V dc, $I_E = 0$) ($V_{CB} = 50$ V dc, $I_E = 0$, $T_A = 150°C$) ($V_{CB} = 60$ V dc, $I_E = 0$, $T_A = 150°C$)	Non-A Suffix A-Suffix, 2N5581, 2N5582 Non-A Suffix A-Suffix, 2N5581, 2N5582	I_{CBO}	— — — —	0.01 0.01 10 10	μA dc
Emitter cutoff current ($V_{EB} = 3.0$ V dc, $I_C = 0$)	A-Suffix, 2N5581, 2N5582	I_{EBO}	—	10	nA dc
Base cutoff current ($V_{CE} = 60$ V dc, $V_{EB(off)} = 3.0$ V dc)	A-Suffix	I_{BL}	—	20	nA dc
On Characteristics					
DC current gain ($I_C = 0.1$ mA dc, $V_{CE} = 10$ V dc)	2N2218,A, 2N2221,A, 2N5581(1) 2N2219,A, 2N2222,A, 2N5582(1)	h_{FE}	20 35	— —	—
($I_C = 1.0$ mA dc, $V_{CE} = 10$ V dc)	2N2218,A, 2N2221,A, 2N5581 2N2219,A, 2N2222,A, 2N5582		25 50	— —	
($I_C = 10$ mA dc, $V_{CE} = 10$ V dc)	2N2218,A, 2N2221,A, 2N5581(1) 2N2219,A, 2N2222,A, 2N5582(1)		35 75	— —	
($I_C = 10$ mA dc, $V_{CE} = 10$ V dc, $T_A = -55°C$)	2N2218,A, 2N2221,A, 2N5581 2N2219,A, 2N2222,A, 2N5582		15 35	— —	
($I_C = 150$ mA dc, $V_{CE} = 10$ V dc)	2N2218,A, 2N2221,A, 2N5581 2N2219,A, 2N2222,A, 2N5582		40 100	120 300	
($I_C = 150$ mA dc, $V_{CE} = 1.0$ V dc)	2N2218,A, 2N2221,A, 2N5581 2N2219,A, 2N2222,A, 2N5582		20 50	— —	
($I_C = 500$ mA dc, $V_{CE} = 10$ V dc)	2N2218, 2N2221 2N2219, 2N2222 2N2218A, 2N2221A, 2N5581 2N2219A, 2N2222A, 2N5582		20 30 25 40	— — — —	
Collector-Emitter saturation voltage ($I_C = 150$ mA dc, $I_B = 15$ mA dc)	Non-A Suffix A-Suffix, 2N5581, 2N5582	$V_{CE(sat)}$	— —	0.4 0.3	V dc
($I_C = 500$ mA dc, $I_B = 50$ mA dc)	Non-A Suffix A-Suffix, 2N5581, 2N5582		— —	1.6 1.0	
Base-Emitter saturation voltage ($I_C = 150$ mA dc, $I_B = 15$ mA dc)	Non-A Suffix A-Suffix, 2N5581, 2N5582	$V_{BE(sat)}$	0.6 0.6	1.3 1.2	V dc
($I_C = 500$ mA dc, $I_B = 50$ mA dc)	Non-A Suffix A-Suffix, 2N5581, 2N5582		— —	2.6 2.0	

▲ FIGURE 5–49

Partial datasheet for 2N2218A–2N2222A.

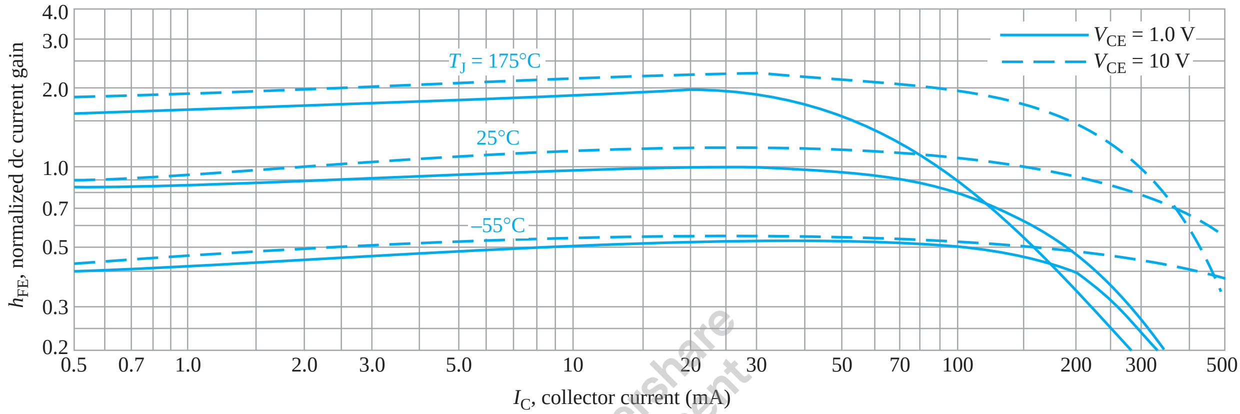
48. Design a circuit using emitter bias that operates from dc voltages of +12 V and −12 V. The maximum I_{CC} is to be 20 mA and the Q-point is at 10 mA and 4 V. The transistor is a 2N3904.

49. Design a circuit using voltage-divider bias for the following specifications: $V_{CC} = 9$ V, $I_{CC(max)} = 5$ mA, $I_C = 1.5$ mA, and $V_{CE} = 3$ V. The transistor is a 2N3904.

50. Design a collector-feedback circuit using a 2N2222A with $V_{CC} = 5$ V, $I_C = 10$ mA, and $V_{CE} = 1.5$ V.

51. Can you replace the 2N3904 in Figure 5–47 with a 2N2222A and maintain the same range of output voltage over a temperature range from 45°C to 55°C?

52. Refer to the datasheet graph in Figure 5–50 and the partial datasheet in Figure 5–49. Determine the minimum dc current gain for a 2N2222A at −55°C, 25°C, and 175°C for $V_{CE} = 1$ V.



▲ FIGURE 5–50

53. A design change is required in the valve interface circuit of the temperature-control system shown in Figure 5–28. The new design will have a valve interface input resistance of 10 kΩ. Determine the effect this change has on the temperature-to-voltage conversion circuit.

54. Investigate the feasibility of redesigning the temperature-to-voltage conversion circuit in Figure 5–29 to operate from a dc supply voltage of 5.1 V and produce the same range of output voltages determined in the Application Activity over the required thermistor temperature range from 60°C to 80°C.

MULTISIM TROUBLESHOOTING PROBLEMS

These file circuits are in the Troubleshooting Problems folder on the companion website.

55. Open file TSP05-55 and determine the fault.

56. Open file TSP05-56 and determine the fault.

57. Open file TSP05-57 and determine the fault.

58. Open file TSP05-58 and determine the fault.

59. Open file TSP05-59 and determine the fault.

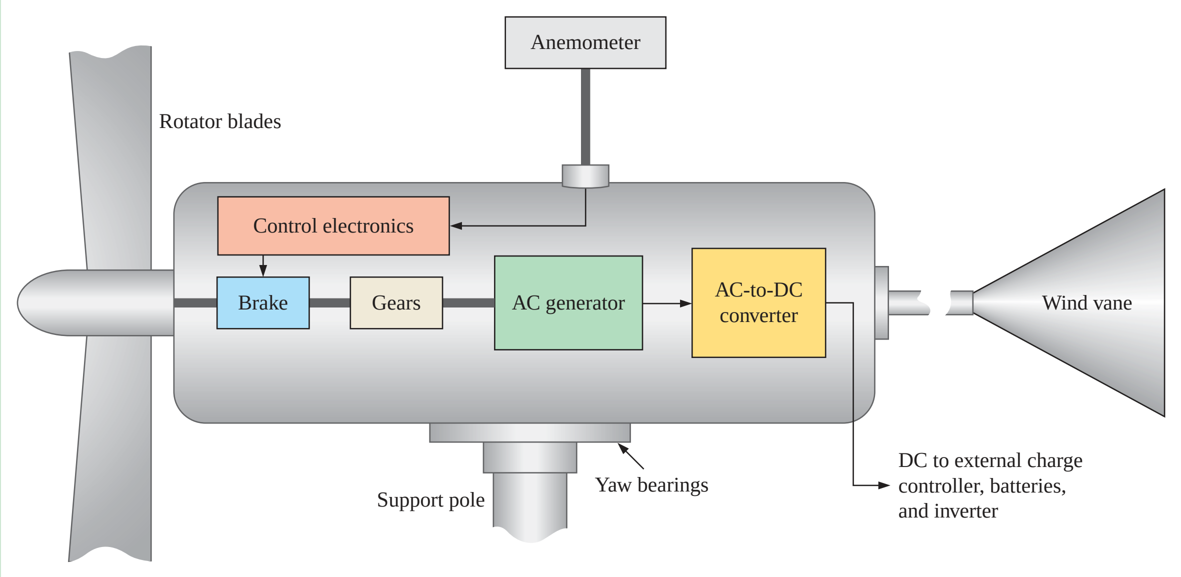
60. Open file TSP05-60 and determine the fault.

GreenTech Application 5: *Wind Power*

Wind energy, like solar energy, is a major renewable resource. Wind is actually a product of solar energy because differences in earth temperatures result in the movement of air. Wind turbines harvest energy from the wind and may be used as small single units to supply an individual home or wind farms where tens to hundreds of large units harvest wind energy and convert it to electricity.

Two key elements in a wind turbine are the blades and the ac generator. In many wind turbines, electronic circuits sense the wind direction and speed and adjust the orientation and pitch of the blades to maximize the energy collected from the wind. The generator produces a varying ac voltage that depends on the rotational speed of the blades due to the wind. Since the frequency and amplitude of a generator output varies with wind speed, the ac output is converted to dc and then back to 60 Hz ac with an inverter. Like a solar power system, the energy can be stored in batteries using a charge controller for smaller applications, or the energy can be connected directly to the grid for large-scale applications.

Figure GA5–1 shows a basic diagram of a horizontal-axis wind turbine (HAWT) for small power applications, such as home use. A typical wind turbine has three blades and is mounted on a very high support tower. Wind energy is converted to mechanical energy by the rotating blades. As shown in Figure GA5–1, the blade rotation is applied to a shaft, which is geared up to turn the ac generator shaft at a higher rate than the blades are rotating. The generator rotation produces an ac voltage output with a frequency that depends on the rate of rotation. Since it is a variable frequency and amplitude output, as previously mentioned, the ac is converted to dc by the ac-to-dc converter. The dc is sent to a charge controller that charges the storage batteries. The battery output is applied to an inverter where it is converted to a 120 V, 60 Hz ac voltage for individual consumer use. The wind vane and yaw bearing assembly are used on small turbines to keep the blades pointed into the wind. An anemometer senses the wind speed in order to brake the blades when the wind reaches a specified speed. This prevents mechanical damage if the wind speed is too high.

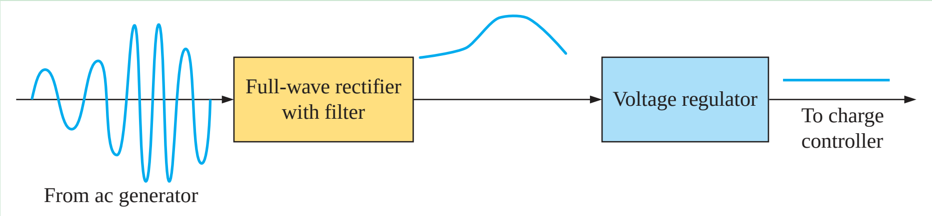


▲ **FIGURE GA5–1**

Basic small HAWT system operation.

The AC-to-DC Converter

Because of the variable frequency of the ac from the generator, it must first be converted to dc for the charge controller. A rectifier and regulator are used for the conversion, as illustrated in Figure GA5–2. The ac voltage from the generator varies in amplitude and frequency as a function of wind speed. The ac-to-dc converter changes the varying ac to a varying dc voltage, which is then applied to a voltage regulator to produce a specified constant dc voltage, as shown.

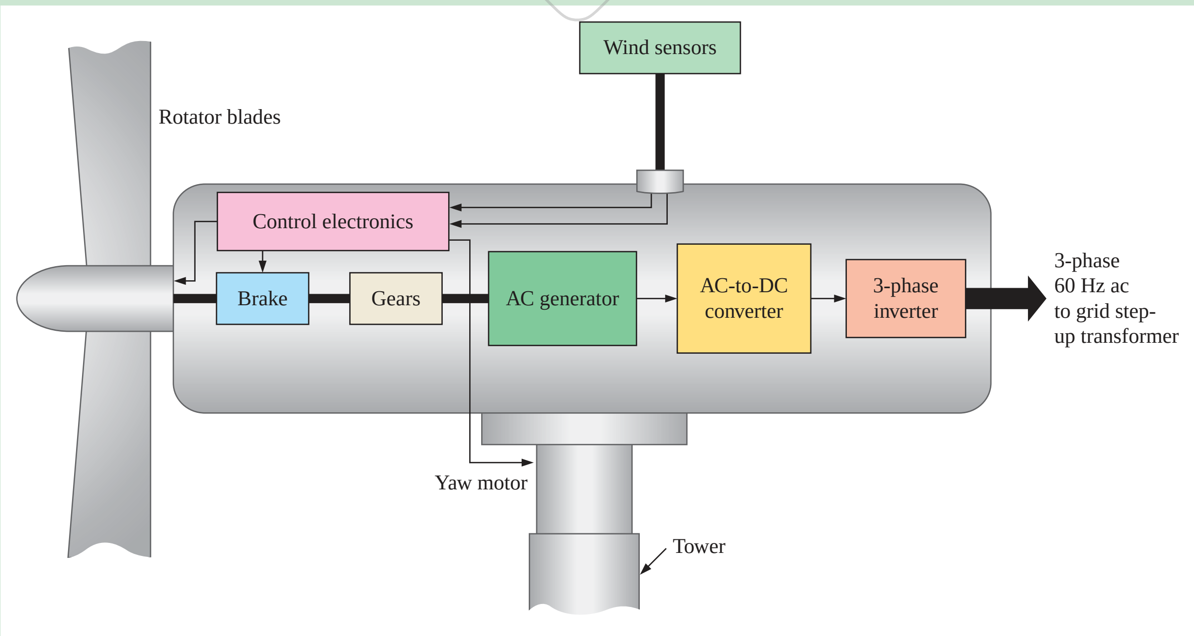


▲ FIGURE GA5–2

AC-to-DC converter block diagram.

Large-Scale Wind Turbines

Figure GA5–3 is a horizontal axis grid-tie turbine, which is the most common configuration for commercial wind farm applications. The wind direction sensor sends a signal to the control electronics so the yaw motor can keep the turbine pointing into the wind. The wind speed sensor sends a signal to the control electronics so the pitch of the blades can be adjusted for maximum efficiency. Also, when the wind exceeds a specified speed, the control electronics activates the brakes to reduce or stop rotation of the blades, preventing damage to the unit.



▲ FIGURE GA5–3

Large horizontal-axis wind turbine (HAWT).

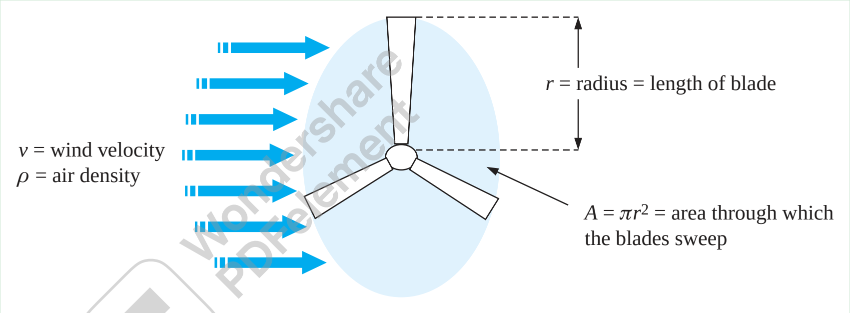
For large wind turbines (above 100 kW–150 kW) the voltage generated is usually 690 V three-phase ac. The output goes to a transformer usually located in the tower or near its base and is stepped up to thousands of volts depending on the requirements of the local electrical grid.

Power in the Wind

The amount of power available in the wind can be calculated using the following formula:

$$P = \frac{\rho A v^3}{2}$$

In the formula, ρ is the density of the air, A is the area swept by the blades, and v is the velocity (speed) of the wind. Note that the power is dependent on the length of the blades, r, and the cube of the wind speed, v^3. Since $A = \pi r^2$, if the length of the blades is doubled, the available power in the wind will be increased by four times ($2^2 = 4$). If the wind velocity doubles, the available power in the wind is increased by eight times ($2^3 = 8$). Of course, a turbine cannot convert all of the available wind power into mechanical power to turn the generator. In fact, most practical turbines can convert less than 50% of the wind power. Figure GA5–4 illustrates the factors that affect the amount of power that can be extracted from the wind.



▲ FIGURE GA5–4

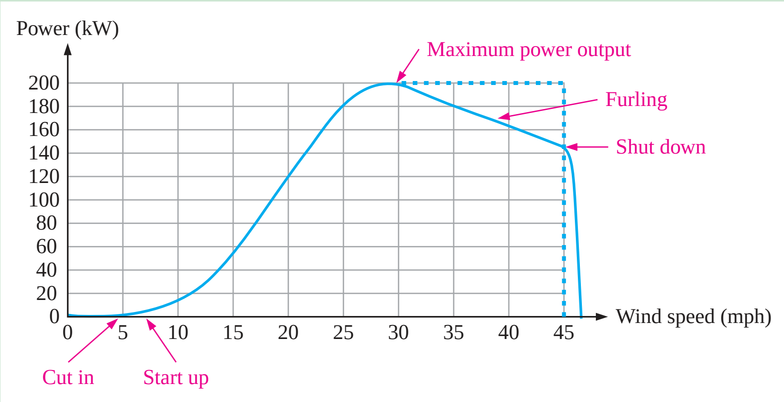
Factor determining the available power in the wind.

Betz Law This law states that the theoretical limit of the amount of power that can be extracted from the wind is 59% if all conditions are perfect. This limiting factor was developed by Albert Betz in 1926. In practice, 20% to 40% can normally be expected.

Wind Power Curve

A wind power curve shows the amount of power that can be extracted over a range of wind speeds (velocities) for specific turbines. Wind power curves will vary from one type of turbine to another. Figure GA5–5 shows a typical curve. The *cut-in speed* is the wind speed at which the blades begin to turn. The *start-up speed* is the wind speed at which the blades are moving fast enough to cause the generator to produce electricity. The start-up speed is slightly higher than the cut-in speed. The *maximum power output* is the peak power that the turbine can produce. For this example curve, the maximum power output is approximately 200 kW at a wind speed of approximately 28 mph.

To limit the rotational speed of the blades above the maximum power output (MPO) point in order to prevent damage to the machine, a process called *furling* is used. Ideally, the curve is kept as level as possible as shown by the dashed portion of the curve in Figure GA5–5. However, in practice, the power decreases above that point, once the furling process is activated. Furling can be accomplished by changing the pitch of the blades or turning the entire turbine away from the wind direction slightly under direction of the control electronics. Also, when the wind reaches a predetermined maximum, the turbine can be completely shut down. For example, the curve shows this turbine being shut down at 45 mph.



▲ **FIGURE GA5–5**

Example of a wind power curve for a wind turbine.

Questions

Some questions may require research beyond the content of this coverage. Answers are at the end of the book.

1. What does HAWT stand for?
2. Why does the input voltage to the ac-to-dc converter vary in amplitude and frequency?
3. What are the physical factors that determine the amount of power available in the wind that strikes the blades of a turbine?
4. What is the Betz limit?
5. In wind farms, how close together should the turbines generally be placed?

The following websites are recommended for viewing HAWTs in action. Many other websites are also available.

http://www.youtube.com/watch?v=eXejxcW-XGo

http://www.youtube.com/watch?v=RFPj9frhKuo

http://www.youtube.com/watch?v=7PLvr-lpADM&NR=1

http://www.youtube.com/watch?v=7rlVMJgPRc4

http://www.youtube.com/watch?v=NeVClBaQI_Q

http://www.youtube.com/watch?v=PEEAl9laoUg

http://www.youtube.com/watch?v=N9_FKGxD27g

http://www.youtube.com/watch?v=v05MuBseBQE

http://www.youtube.com/watch?v=hBRfboAscww

BJT AMPLIFIERS

6

CHAPTER OUTLINE

6–1 Amplifier Operation
6–2 Transistor AC Models
6–3 The Common-Emitter Amplifier
6–4 The Common-Collector Amplifier
6–5 The Common-Base Amplifier
6–6 Multistage Amplifiers
6–7 The Differential Amplifier
6–8 Troubleshooting
Application Activity
GreenTech Application 6: *Wind Power*

CHAPTER OBJECTIVES

- Describe amplifier operation
- Discuss transistor models
- Describe and analyze the operation of common-emitter amplifiers
- Describe and analyze the operation of common-collector amplifiers
- Describe and analyze the operation of common-base amplifiers
- Describe and analyze the operation of multistage amplifiers
- Discuss the differential amplifier and its operation
- Troubleshoot amplifier circuits

KEY TERMS

- *r* parameter
- Common-emitter
- ac ground
- Input resistance
- Output resistance
- Attenuation
- Bypass capacitor
- Common-collector
- Emitter-follower
- Common-base
- Decibel
- Differential amplifier
- Common mode
- CMRR (Common-mode rejection ratio)

APPLICATION ACTIVITY PREVIEW

The Application Activity in this chapter involves a preamplifier circuit for a public address system. The complete system includes the preamplifier, a power amplifier, and a dc power supply. You will focus on the preamplifier in this chapter and then on the power amplifier in Chapter 7.

VISIT THE COMPANION WEBSITE

Study aids and Multisim files for this chapter are available at http://www.pearsonhighered.com/electronics

INTRODUCTION

The things you learned about biasing a transistor in Chapter 5 are now applied in this chapter where bipolar junction transistor (BJT) circuits are used as small-signal amplifiers. The term *small-signal* refers to the use of signals that take up a relatively small percentage of an amplifier's operational range. Additionally, you will learn how to reduce an amplifier to an equivalent dc and ac circuit for easier analysis, and you will learn about multistage amplifiers. The differential amplifier is also covered.

6–1 AMPLIFIER OPERATION

The biasing of a transistor is purely a dc operation. The purpose of biasing is to establish a Q-point about which variations in current and voltage can occur in response to an ac input signal. In applications where small signal voltages must be amplified—such as from an antenna or a microphone—variations about the Q-point are relatively small. Amplifiers designed to handle these small ac signals are often referred to as *small-signal amplifiers.*

After completing this section, you should be able to

- **Describe amplifier operation**
- Identify ac quantities
  - Distinguish ac quantities from dc quantities
- Discuss the operation of a linear amplifier
  - Define *phase inversion*
  - Graphically illustrate amplifier operation
  - Analyze ac load line operation

HISTORY NOTE

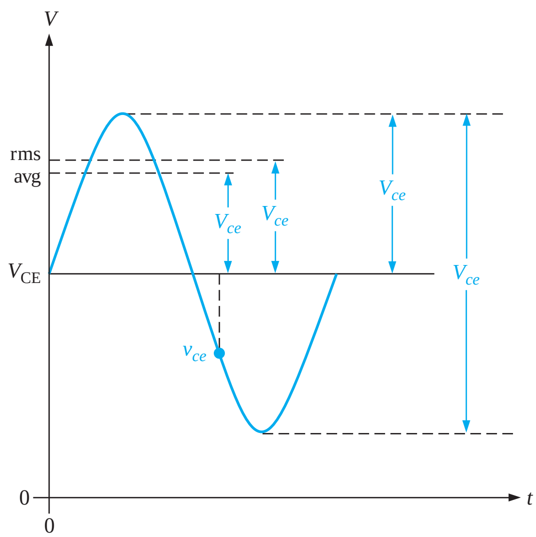
The American inventor Lee De Forest (1873–1961) is one of several pioneers of radio development. De Forest experimented with receiving long-distance radio signals and in 1907 patented an electronic device named the *audion,* which was the first amplifier. De Forest's new three-electrode (triode) vacuum tube boosted radio waves as they were received and made possible what was then called "wireless telephony," which allowed the human voice, music, or any broadcast signal to be heard.

AC Quantities

In the previous chapters, dc quantities were identified by nonitalic uppercase (capital) subscripts such as I_C, I_E, V_C, and V_{CE}. Lowercase italic subscripts are used to indicate ac quantities of rms, peak, and peak-to-peak currents and voltages: for example, I_c, I_e, I_b, V_c, and V_{ce} (rms values are assumed unless otherwise stated). Instantaneous quantities are represented by both lowercase letters and subscripts such as i_c, i_e, i_b, and v_{ce}. Figure 6–1 illustrates these quantities for a specific voltage waveform.

▶ **FIGURE 6–1**

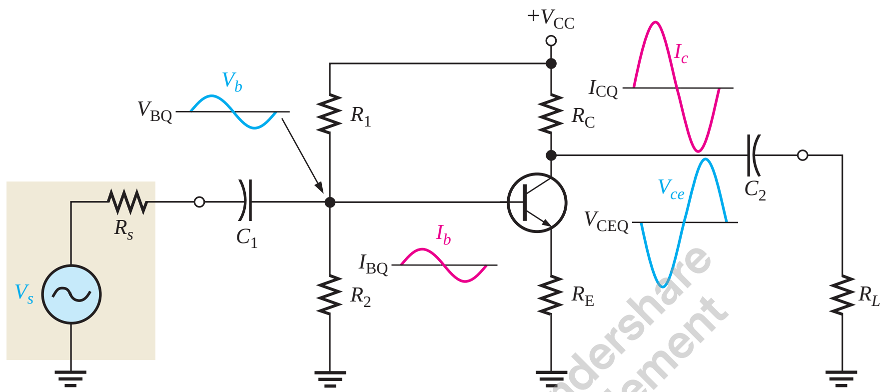
V_{ce} can represent rms, average, peak, or peak-to-peak, but rms will be assumed unless stated otherwise. v_{ce} can be any instantaneous value on the curve.



In addition to currents and voltages, resistances often have different values when a circuit is analyzed from an ac viewpoint as opposed to a dc viewpoint. Lowercase subscripts are used to identify ac resistance values. For example, R_c is the ac collector resistance, and R_C is the dc collector resistance. You will see the need for this distinction later. Resistance values *internal* to the transistor use a lowercase r' to show it is an ac resistance. An example is the internal ac emitter resistance, r'_e.

The Linear Amplifier

A linear amplifier provides amplification of a signal without any distortion so that the output signal is an exact amplified replica of the input signal. A voltage-divider biased transistor with a sinusoidal ac source capacitively coupled to the base through C_1 and a load capacitively coupled to the collector through C_2 is shown in Figure 6–2. The coupling capacitors block dc and thus prevent the internal source resistance, R_s, and the load resistance, R_L, from changing the dc bias voltages at the base and collector. The capacitors ideally appear as shorts to the signal voltage. The sinusoidal source voltage causes the base voltage to vary sinusoidally above and below its dc bias level, V_{BQ}. The resulting variation in base current produces a larger variation in collector current because of the current gain of the transistor.

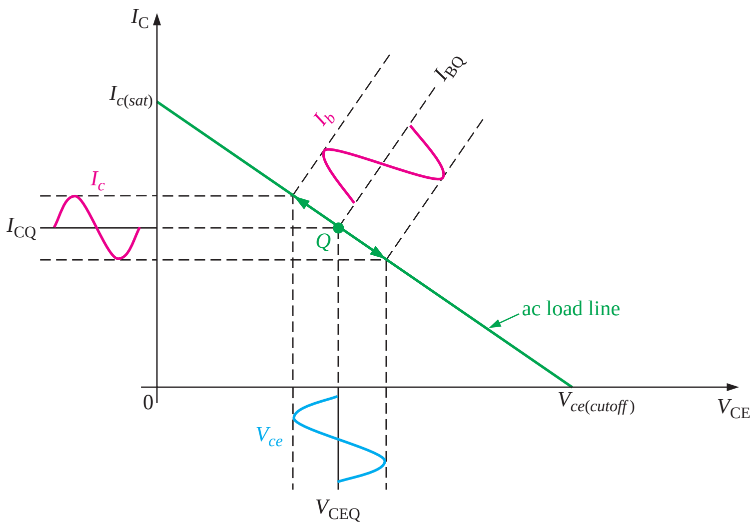


◀ **FIGURE 6–2**

An amplifier with voltage-divider bias driven by an ac voltage source with an internal resistance, R_s.

As the sinusoidal collector current increases, the collector voltage decreases. The collector current varies above and below its Q-point value, I_{CQ}, in phase with the base current. The sinusoidal collector-to-emitter voltage varies above and below its Q-point value, V_{CEQ}, 180° out of phase with the base voltage, as illustrated in Figure 6–2. A transistor always produces a **phase inversion** between the base voltage and the collector voltage.

A Graphical Picture The operation just described can be illustrated graphically on the ac load line, as shown in Figure 6–3. The sinusoidal voltage at the base produces a base current that varies above and below the Q-point on the ac load line, as shown by the arrows.



◀ **FIGURE 6–3**

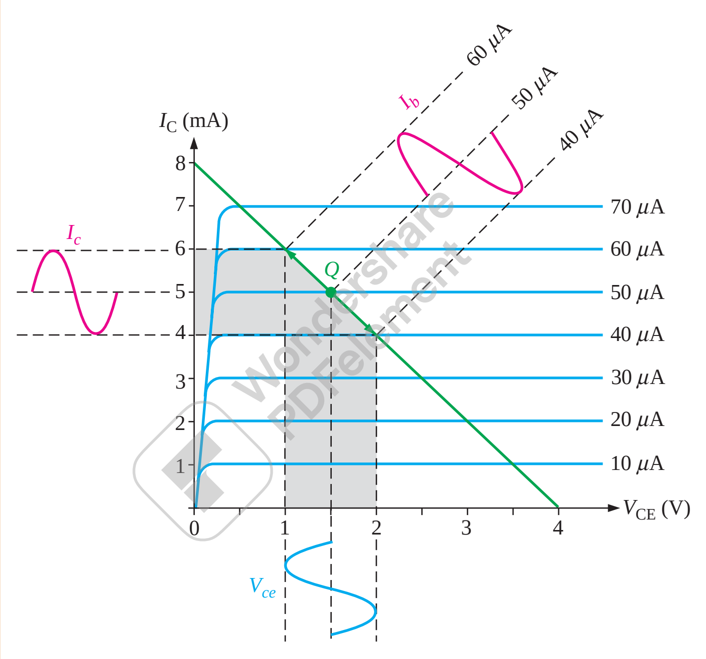
Graphical ac load line operation of the amplifier showing the variation of the base current, collector current, and collector-to-emitter voltage about their dc Q-point values. I_b and I_c are on different scales.

Lines projected from the peaks of the base current, across to the I_C axis, and down to the V_{CE} axis, indicate the peak-to-peak variations of the collector current and collector-to-emitter voltage, as shown. The ac load line differs from the dc load line because the effective ac collector resistance is R_L in parallel with R_C and is less than the dc collector resistance R_C alone. This difference between the dc and the ac load lines is covered in Chapter 7 in relation to power amplifiers.

EXAMPLE 6–1

The ac load line operation of a certain amplifier extends 10 μA above and below the Q-point base current value of 50 μA, as shown in Figure 6–4. Determine the resulting peak-to-peak values of collector current and collector-to-emitter voltage from the graph.

▶ FIGURE 6–4



Solution Projections on the graph of Figure 6–4 show the collector current varying from 6 mA to 4 mA for a peak-to-peak value of **2 mA** and the collector-to-emitter voltage varying from 1 V to 2 V for a peak-to-peak value of **1 V**.

*Related Problem** What are the Q-point values of I_C and V_{CE} in Figure 6–4?

*Answers can be found at www.pearsonhighered.com/floyd.

SECTION 6–1 CHECKUP
Answers can be found at www.pearsonhighered.com/floyd.

1. When I_b is at its positive peak, I_c is at its _____ peak, and V_{ce} is at its _____ peak.
2. What is the difference between V_{CE} and V_{ce}?
3. What is the difference between R_e and r'_e?

6–2 Transistor AC Models

To visualize the operation of a transistor in an amplifier circuit, it is often useful to represent the device by a model circuit. A transistor model circuit uses various internal transistor parameters to represent its operation. Transistor models are described in this section based on resistance or *r* parameters. Another system of parameters, called *h* parameters, is briefly described.

After completing this section, you should be able to

- **Discuss transistor models**
- List and define the *r* parameters
- Describe the *r*-parameter transistor model
- Determine r'_e using a formula
- Compare ac beta and dc beta
- List and define the *h* parameters

r Parameters

The five *r* parameters commonly used for BJTs are given in Table 6–1. The italic lowercase letter *r* with a prime denotes resistances internal to the transistor.

TABLE 6–1

r parameters.

r PARAMETER	DESCRIPTION
α_{ac}	ac alpha (I_c/I_e)
β_{ac}	ac beta (I_c/I_b)
r'_e	ac emitter resistance
r'_b	ac base resistance
r'_c	ac collector resistance

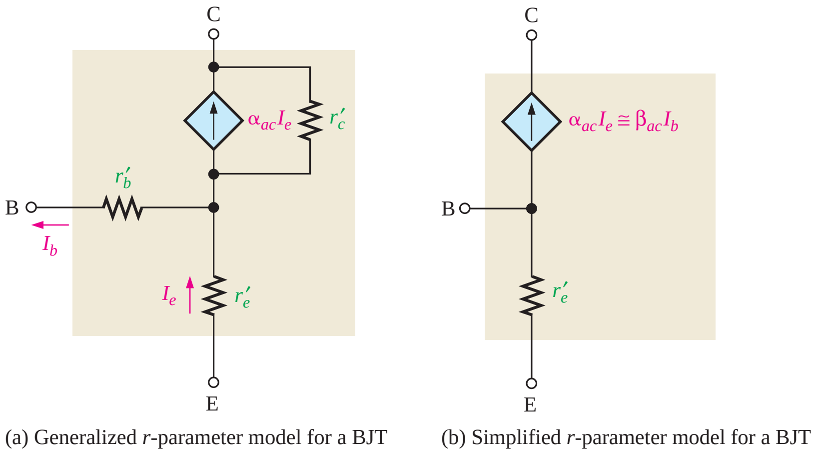
r-Parameter Transistor Model

An ***r*-parameter** model for a BJT is shown in Figure 6–5(a). For most general analysis work, it can be simplified as follows: The effect of the ac base resistance (r'_b) is usually small enough to neglect, so it can be replaced by a short. The ac collector resistance (r'_c) is usually several hundred kilohms and can be replaced by an open. The resulting simplified *r*-parameter equivalent circuit is shown in Figure 6–5(b).

The interpretation of this model circuit in terms of a transistor's ac operation is as follows: A resistance (r'_e) appears between the emitter and base terminals. This is the resistance "seen" looking into the emitter of a forward-biased transistor. The collector effectively acts as a dependent current source of $\alpha_{ac}I_e$ or, equivalently, $\beta_{ac}I_b$, represented by the diamond-shaped symbol. These factors are shown with a transistor symbol in Figure 6–6.

Determining r'_e by a Formula

For amplifier analysis, the ac emitter resistance, r'_e, is the most important of the *r* parameters. To calculate the approximate value of r'_e, you can use Equation 6–1, which is derived

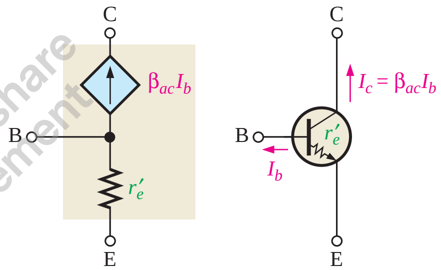


▲ **FIGURE 6–5**

r-parameter transistor model.

► **FIGURE 6–6**

Relation of transistor symbol to *r*-parameter model.



assuming an abrupt junction between the *n* and *p* regions. It is also temperature dependent and is based on an ambient temperature of 20°C.

Equation 6–1

$$r'_e \cong \frac{25\text{ mV}}{I_E}$$

The numerator will be slightly larger for higher temperatures or transistors with a gradual (instead of an abrupt) junction. Although these cases will yield slightly different results, most designs are not critically dependent on the value of r'_e, and you will generally obtain excellent agreement with actual circuits using the equation as given. The derivation for Equation 6–1 can be found in "Derivations of Selected Equations" at www.pearsonhighered.com/floyd.

EXAMPLE 6–2 Determine the r'_e of a transistor that is operating with a dc emitter current of 2 mA.

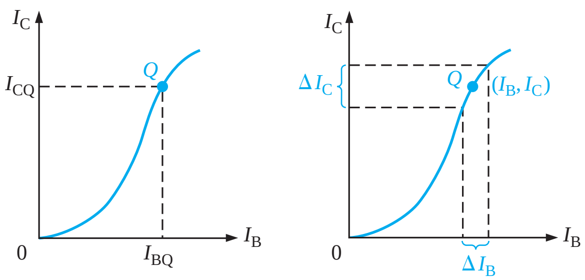
Solution

$$r'_e \cong \frac{25\text{ mV}}{I_E} = \frac{25\text{ mV}}{2\text{ mA}} = \mathbf{12.5\ \Omega}$$

Related Problem What is I_E if $r'_e = 8\ \Omega$?

Comparison of the AC Beta (β_{ac}) to the DC Beta (β_{DC})

For a typical transistor, a graph of I_C versus I_B is nonlinear, as shown in Figure 6–7(a). If you pick a Q-point on the curve and cause the base current to vary an amount ΔI_B, then the collector current will vary an amount ΔI_C as shown in part (b). At different points on the nonlinear curve, the ratio $\Delta I_C/\Delta I_B$ will be different, and it may also differ from the I_C/I_B ratio at the Q-point. Since $\beta_{DC} = I_C/I_B$ and $\beta_{ac} = \Delta I_C/\Delta I_B$, the values of these two quantities can differ slightly.



(a) $\beta_{DC} = I_C/I_B$ at Q-point (b) $\beta_{ac} = \Delta I_C/\Delta I_B$

FIGURE 6–7

I_C-versus-I_B curve illustrates the difference between $\beta_{DC} = I_C/I_B$ and $\beta_{ac} = \Delta I_C/\Delta I_B$.

h Parameters

A manufacturer's datasheet typically specifies *h* (hybrid) parameters (h_i, h_r, h_f, and h_o) because they are relatively easy to measure.

The four basic ac *h* parameters and their descriptions are given in Table 6–2. Each of the four *h* parameters carries a second subscript letter to designate the common-emitter (*e*), common-base (*b*), or common-collector (*c*) amplifier configuration, as listed in Table 6–3. The term *common* refers to one of the three terminals (E, B, or C) that is referenced to ac ground for both input and output signals. The characteristics of each of these three BJT amplifier configurations are covered later in this chapter.

TABLE 6–2

Basic ac *h* parameters.

h PARAMETER	DESCRIPTION	CONDITION
h_i	Input impedance (resistance)	Output shorted
h_r	Voltage feedback ratio	Input open
h_f	Forward current gain	Output shorted
h_o	Output admittance (conductance)	Input open

TABLE 6–3

Subscripts of *h* parameters for each of the three amplifier configurations.

CONFIGURATION	*h* PARAMETERS
Common-Emitter	h_{ie}, h_{re}, h_{fe}, h_{oe}
Common-Base	h_{ib}, h_{rb}, h_{fb}, h_{ob}
Common-Collector	h_{ic}, h_{rc}, h_{fc}, h_{oc}

Relationships of *h* Parameters and *r* Parameters

The ac current ratios, α_{ac} and β_{ac}, convert directly from *h* parameters as follows:

$$\alpha_{ac} = h_{fb}$$
$$\beta_{ac} = h_{fe}$$

Because datasheets often provide only common-emitter h parameters, the following formulas show how to convert them to r parameters. We will use r parameters throughout the text because they are easier to apply and more practical.

$$r'_e = \frac{h_{re}}{h_{oe}}$$

$$r'_c = \frac{h_{re} + 1}{h_{oe}}$$

$$r'_b = h_{ie} - \frac{h_{re}}{h_{oe}}(1 + h_{fe})$$

SECTION 6–2 CHECKUP

1. Define each of the parameters: α_{ac}, β_{ac}, r'_e, r'_b, and r'_c.
2. Which h parameter is equivalent to β_{ac}?
3. If $I_E = 15$ mA, what is the approximate value of r'_e?

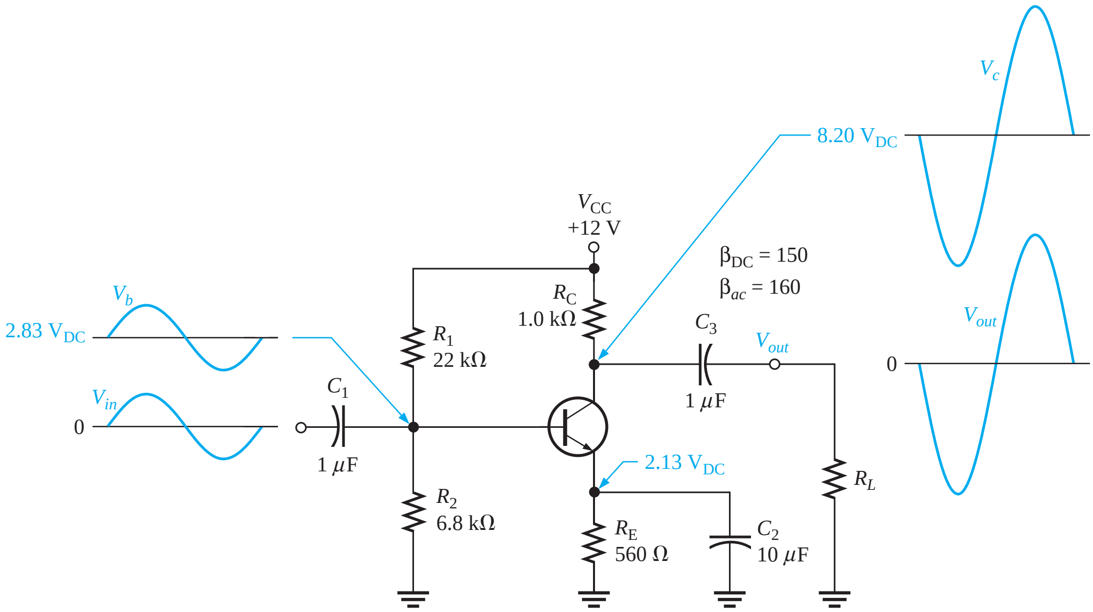
6–3 THE COMMON-EMITTER AMPLIFIER

As you have learned, a BJT can be represented in an ac model circuit. Three amplifier configurations are the common-emitter, the common-base, and the common-collector. The common-emitter (CE) configuration has the emitter as the common terminal, or ground, to an ac signal. CE amplifiers exhibit high voltage gain and high current gain. The common-collector and common-base configurations are covered in the sections 6–4 and 6–5.

After completing this section, you should be able to

- **Describe and analyze the operation of common-emitter amplifiers**
- Discuss a common-emitter amplifier with voltage-divider bias
  ◆ Show input and output signals ◆ Discuss phase inversion
- Perform a dc analysis
  ◆ Represent the amplifier by its dc equivalent circuit
- Perform an ac analysis
  ◆ Represent the amplifier by its ac equivalent circuit ◆ Define *ac ground* ◆ Discuss the voltage at the base ◆ Discuss the input resistance at the base and the output resistance
- Analyze the amplifier for voltage gain
  ◆ Define *attenuation* ◆ Define *bypass capacitor* ◆ Describe the effect of an emitter bypass capacitor on voltage gain ◆ Discuss voltage gain without a bypass capacitor ◆ Explain the effect of a load on voltage gain
- Discuss the stability of the voltage gain
  ◆ Define *stability* ◆ Explain the purpose of swamping r'_e and the effect on input resistance
- Determine current gain and power gain

Figure 6–8 shows a **common-emitter** amplifier with voltage-divider bias and coupling capacitors C_1 and C_3 on the input and output and a bypass capacitor, C_2, from emitter to ground. The input signal, V_{in}, is capacitively coupled to the base terminal, the output signal, V_{out}, is capacitively coupled from the collector to the load. The amplified output is 180° out of phase with the input. Because the ac signal is applied to the base terminal as



▲ **FIGURE 6–8**

A common-emitter amplifier.

the input and taken from the collector terminal as the output, the emitter is common to both the input and output signals. There is no signal at the emitter because the bypass capacitor effectively shorts the emitter to ground at the signal frequency. All amplifiers have a combination of both ac and dc operation, which must be considered, but keep in mind that the common-emitter designation refers to the ac operation.

Phase Inversion The output signal is 180° out of phase with the input signal. As the input signal voltage changes, it causes the ac base current to change, resulting in a change in the collector current from its Q-point value. If the base current increases, the collector current increases above its Q-point value, causing an increase in the voltage drop across R_C. This increase in the voltage across R_C means that the voltage at the collector decreases from its Q-point. So, any change in input signal voltage results in an opposite change in collector signal voltage, which is a phase inversion.

DC Analysis

To analyze the amplifier in Figure 6–8, the dc bias values must first be determined. To do this, a dc equivalent circuit is developed by removing the coupling and bypass capacitors because they appear open as far as the dc bias is concerned. This also removes the load resistor and signal source. The dc equivalent circuit is shown in Figure 6–9.

Theveninizing the bias circuit and applying Kirchhoff's voltage law to the base-emitter circuit,

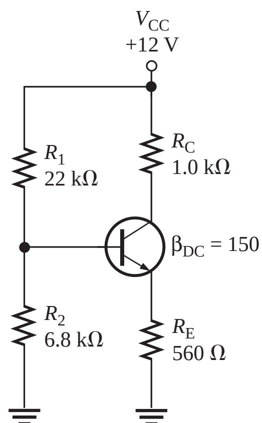
$$R_{TH} = \frac{R_1 R_2}{R_1 + R_2} = \frac{(6.8\ \text{k}\Omega)(22\ \text{k}\Omega)}{6.8\ \text{k}\Omega + 22\ \text{k}\Omega} = 5.19\ \text{k}\Omega$$

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\frac{6.8\ \text{k}\Omega}{6.8\ \text{k}\Omega + 22\ \text{k}\Omega}\right)12\ \text{V} = 2.83\ \text{V}$$

$$I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}} = \frac{2.83\ \text{V} - 0.7\ \text{V}}{560\ \Omega + 34.6\ \Omega} = 3.58\ \text{mA}$$

$$I_C \cong I_E = 3.58\ \text{mA}$$

$$V_E = I_E R_E = (3.58\ \text{mA})(560\ \Omega) = 2\ \text{V}$$



▲ **FIGURE 6–9**

DC equivalent circuit for the amplifier in Figure 6–8.

$$V_B = V_E + 0.7\text{ V} = 2.7\text{ V}$$
$$V_C = V_{CC} - I_C R_C = 12\text{ V} - (3.58\text{ mA})(1.0\text{ k}\Omega) = 8.42\text{ V}$$
$$V_{CE} = V_C - V_E = 8.42\text{ V} - 2\text{ V} = 6.42\text{ V}$$

AC Analysis

To analyze the ac signal operation of an amplifier, an ac equivalent circuit is developed as follows:

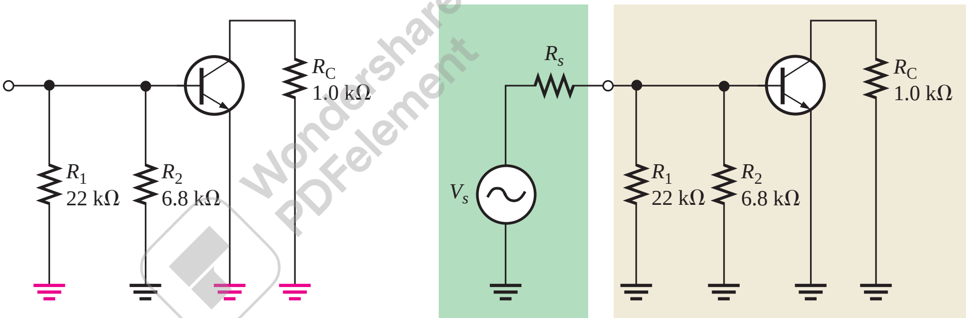
1. The capacitors C_1, C_2, and C_3 are replaced by effective shorts because their values are selected so that X_C is negligible at the signal frequency and can be considered to be 0 Ω.
2. The dc source is replaced by ground.

A dc voltage source has an internal resistance of near 0 Ω because it holds a constant voltage independent of the load (within limits); no ac voltage can be developed across it so it appears as an ac short. This is why a dc source is called an **ac ground**.

The ac equivalent circuit for the common-emitter amplifier in Figure 6–8 is shown in Figure 6–10(a). Notice that both R_C and R_1 have one end connected to ac ground (red) because, in the actual circuit, they are connected to V_{CC} which is, in effect, ac ground.

FIGURE 6–10

AC equivalent circuit for the amplifier in Figure 6–8.



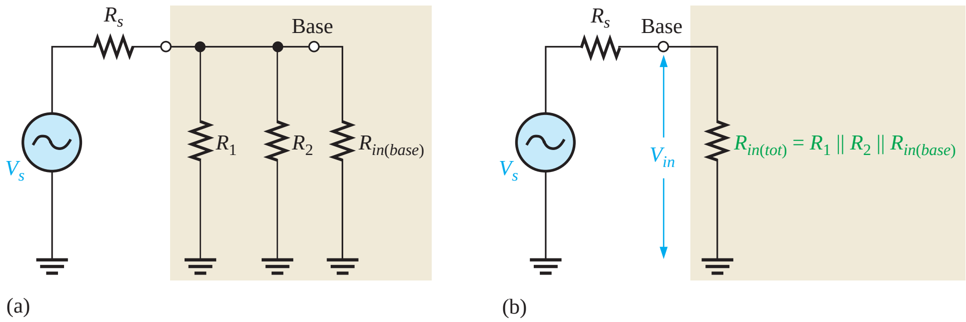
(a) Without an input signal voltage (AC ground is shown in red.)   (b) With an input signal voltage

In ac analysis, the ac ground and the actual ground are treated as the same point electrically. The amplifier in Figure 6–8 is called a common-emitter amplifier because the bypass capacitor C_2 keeps the emitter at ac ground. Ground is the common point in the circuit.

Signal (AC) Voltage at the Base An ac voltage source, V_s, is shown connected to the input in Figure 6–10(b). If the internal resistance of the ac source is 0 Ω, then all of the source voltage appears at the base terminal. If, however, the ac source has a nonzero internal resistance, then three factors must be taken into account in determining the actual signal voltage at the base. These are the *source resistance* (R_s), the *bias resistance* ($R_1 \| R_2$), and the *ac input resistance* at the base of the transistor ($R_{in(base)}$). This is illustrated in Figure 6–11(a) and is simplified by combining R_1, R_2, and $R_{in(base)}$ in parallel to get the total **input resistance**, $R_{in(tot)}$, which is the resistance "seen" by an ac source connected to the input, as shown in Figure 6–11(b). A high value of input resistance is desirable so that the amplifier will not excessively load the signal source. This is opposite to the requirement for a stable Q-point, which requires smaller resistors. The conflicting requirement for high input resistance and stable biasing is but one of the many trade-offs that must be considered when choosing components for a circuit. The total input resistance is expressed by the following formula:

Equation 6–2

$$R_{in(tot)} = R_1 \| R_2 \| R_{in(base)}$$



▲ **FIGURE 6–11**

AC equivalent of the base circuit.

As you can see in the figure, the source voltage, V_s, is divided down by R_s (source resistance) and $R_{in(tot)}$ so that the signal voltage at the base of the transistor is found by the voltage-divider formula as follows:

$$V_b = \left(\frac{R_{in(tot)}}{R_s + R_{in(tot)}}\right)V_s$$

If $R_s \ll R_{in(tot)}$, then $V_b \cong V_s$ where V_b is the input voltage, V_{in}, to the amplifier.

Input Resistance at the Base To develop an expression for the ac input resistance looking in at the base, use the simplified *r*-parameter model of the transistor. Figure 6–12 shows the transistor model connected to the external collector resistor, R_C. The input resistance looking in at the base is

$$R_{in(base)} = \frac{V_{in}}{I_{in}} = \frac{V_b}{I_b}$$

The base voltage is

$$V_b = I_e r'_e$$

and since $I_e \cong I_c$,

$$I_b \cong \frac{I_e}{\beta_{ac}}$$

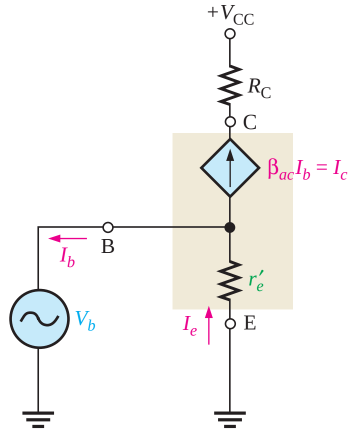
Substituting for V_b and I_b,

$$R_{in(base)} = \frac{V_b}{I_b} = \frac{I_e r'_e}{I_e/\beta_{ac}}$$

Cancelling I_e,

$$\boldsymbol{R_{in(base)} = \beta_{ac} r'_e}$$

Equation 6–3



▲ **FIGURE 6–12**

r-parameter transistor model (inside shaded block) connected to external circuit.

Output Resistance The **output resistance** of the common-emitter amplifier is the resistance looking in at the collector and is approximately equal to the collector resistor.

$$\boldsymbol{R_{out} \cong R_C}$$

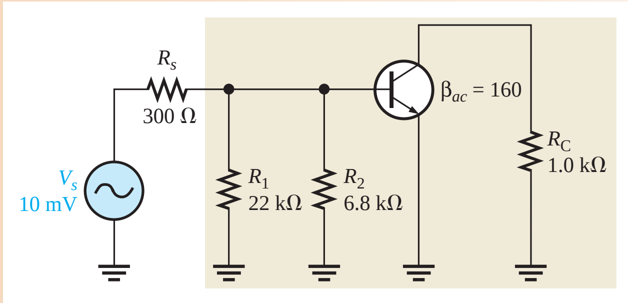
Equation 6–4

Actually, $R_{out} = R_C \parallel r'_c$, but since the internal ac collector resistance of the transistor, r'_c, is typically much larger than R_C, the approximation is usually valid.

EXAMPLE 6–3

Determine the signal voltage at the base of the transistor in Figure 6–13. This circuit is the ac equivalent of the amplifier in Figure 6–8 with a 10 mV rms, 300 Ω signal source. I_E was previously found to be 3.80 mA.

▶ FIGURE 6–13



Solution First, determine the ac emitter resistance.

$$r'_e \cong \frac{25\text{ mV}}{I_E} = \frac{25\text{ mV}}{3.80\text{ mA}} = 6.58\ \Omega$$

Then,

$$R_{in(base)} = \beta_{ac}r'_e = 160(6.58\ \Omega) = 1.05\text{ k}\Omega$$

Next, determine the total input resistance viewed from the source.

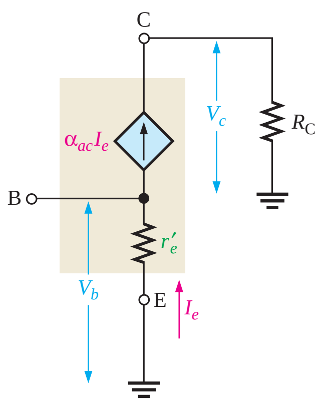
$$R_{in(tot)} = R_1 \parallel R_2 \parallel R_{in(base)} = \frac{1}{\frac{1}{22\text{ k}\Omega} + \frac{1}{6.8\text{ k}\Omega} + \frac{1}{1.05\text{ k}\Omega}} = 873\ \Omega$$

The source voltage is divided down by R_s and $R_{in(tot)}$, so the signal voltage at the base is the voltage across $R_{in(tot)}$.

$$V_b = \left(\frac{R_{in(tot)}}{R_s + R_{in(tot)}}\right)V_s = \left(\frac{873\ \Omega}{1173\ \Omega}\right)10\text{ mV} = \mathbf{7.44\text{ mV}}$$

As you can see, there is significant attenuation (reduction) of the source voltage due to the source resistance and amplifier's input resistance combining to act as a voltage divider.

Related Problem Determine the signal voltage at the base of Figure 6–13 if the source resistance is 75 Ω and another transistor with an ac beta of 200 is used.



▲ FIGURE 6–14

Model circuit for obtaining ac voltage gain.

Voltage Gain

The ac voltage gain expression for the common-emitter amplifier is developed using the model circuit in Figure 6–14. The gain is the ratio of ac output voltage at the collector (V_c) to ac input voltage at the base (V_b).

$$A_v = \frac{V_{out}}{V_{in}} = \frac{V_c}{V_b}$$

Notice in the figure that $V_c = \alpha_{ac}I_eR_C \cong I_eR_C$ and $V_b = I_er'_e$. Therefore,

$$A_v = \frac{I_eR_C}{I_er'_e}$$

The I_e terms cancel, so

Equation 6–5

$$\boldsymbol{A_v = \frac{R_C}{r'_e}}$$

Equation 6–5 is the voltage gain from base to collector. To get the overall gain of the amplifier from the source voltage to collector, the attenuation of the input circuit must be included.

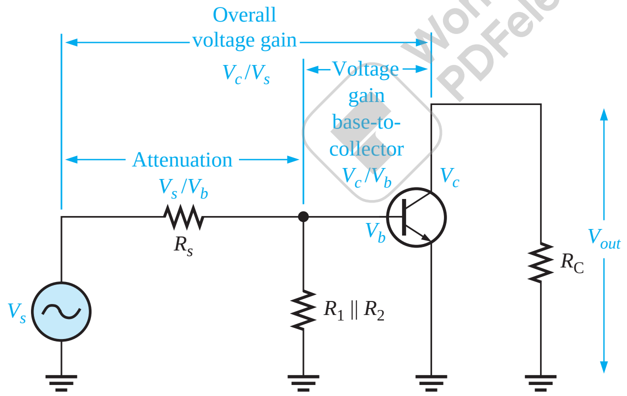
Attenuation is the reduction in signal voltage as it passes through a circuit and corresponds to a gain of less than 1. For example, if the signal amplitude is reduced by half, the attenuation is 2, which can be expressed as a gain of 0.5 because gain is the reciprocal of attenuation. Suppose a source produces a 10 mV input signal and the source resistance combined with the load resistance results in a 2 mV output signal. In this case, the attenuation is 10 mV/2 mV = 5. That is, the input signal is reduced by a factor of 5. This can be expressed in terms of gain as 1/5 = 0.2.

Assume that the amplifier in Figure 6–15 has a voltage gain from base to collector of A_v and the attenuation from the source to the base is V_s/V_b. This attenuation is produced by the source resistance and total input resistance of the amplifier acting as a voltage divider and can be expressed as

$$\text{Attenuation} = \frac{V_s}{V_b} = \frac{R_s + R_{in(tot)}}{R_{in(tot)}}$$

The overall voltage gain of the amplifier, A'_v, is the voltage gain from base to collector, V_c/V_b, times the reciprocal of the attenuation, V_b/V_s.

$$A'_v = \left(\frac{V_c}{V_b}\right)\left(\frac{V_b}{V_s}\right) = \frac{V_c}{V_s}$$



▲ FIGURE 6–15

Base circuit attenuation and overall voltage gain.

Effect of the Emitter Bypass Capacitor on Voltage Gain The emitter **bypass capacitor**, which is C_2 in Figure 6–8, provides an effective short to the ac signal around the emitter resistor, thus keeping the emitter at ac ground, as you have seen. With the bypass capacitor, the gain of a given amplifier is maximum and equal to R_C/r'_e.

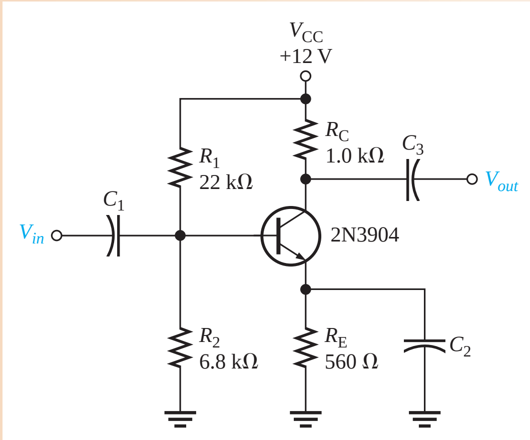
The value of the bypass capacitor must be large enough so that its reactance over the frequency range of the amplifier is very small (ideally 0 Ω) compared to R_E. A good rule-of-thumb is that the capacitive reactance, X_C, of the bypass capacitor should be at least 10 times smaller than R_E at the minimum frequency for which the amplifier must operate.

$$10X_C \leq R_E$$

EXAMPLE 6–4

Select a minimum value for the emitter bypass capacitor, C_2, in Figure 6–16 if the amplifier must operate over a frequency range from 200 Hz to 10 kHz.

▶ **FIGURE 6–16**



Solution The X_C of the bypass capacitor, C_2, should be at least ten times less than R_E.

$$X_{C2} = \frac{R_E}{10} = \frac{560\ \Omega}{10} = 56\ \Omega$$

Determine the capacitance value at the minimum frequency of 200 Hz as follows:

$$C_2 = \frac{1}{2\pi f X_{C2}} = \frac{1}{2\pi(200\ \text{Hz})(56\ \Omega)} = \mathbf{14.2\ \mu F}$$

This is the minimum value for the bypass capacitor for this circuit. You can always use a larger value, although cost and physical size may impose limitations.

Related Problem If the minimum frequency is reduced to 100 Hz, what value of bypass capacitor must you use?

Voltage Gain Without the Bypass Capacitor To see how the bypass capacitor affects ac voltage gain, let's remove it from the circuit in Figure 6–16 and compare voltage gains.

Without the bypass capacitor, the emitter is no longer at ac ground. Instead, R_E is seen by the ac signal between the emitter and ground and effectively adds to r'_e in the voltage gain formula.

Equation 6–6

$$\boldsymbol{A_v = \frac{R_C}{r'_e + R_E}}$$

The effect of R_E is to decrease the ac voltage gain.

EXAMPLE 6–5

Calculate the base-to-collector voltage gain of the amplifier in Figure 6–16 both without and with an emitter bypass capacitor if there is no load resistor.

Solution From Example 6–3, $r'_e = 6.58\ \Omega$ for this same amplifier. Without C_2, the gain is

$$A_v = \frac{R_C}{r'_e + R_E} = \frac{1.0\ \text{k}\Omega}{567\ \Omega} = \mathbf{1.76}$$

With C_2, the gain is

$$A_v = \frac{R_C}{r'_e} = \frac{1.0\text{ k}\Omega}{6.58\ \Omega} = \mathbf{152}$$

As you can see, the bypass capacitor makes quite a difference.

Related Problem Determine the base-to-collector voltage gain in Figure 6–16 with R_E bypassed, for the following circuit values: $R_C = 1.8\text{ k}\Omega$, $R_E = 1.0\text{ k}\Omega$, $R_1 = 33\text{ k}\Omega$, and $R_2 = 6.8\text{ k}\Omega$.

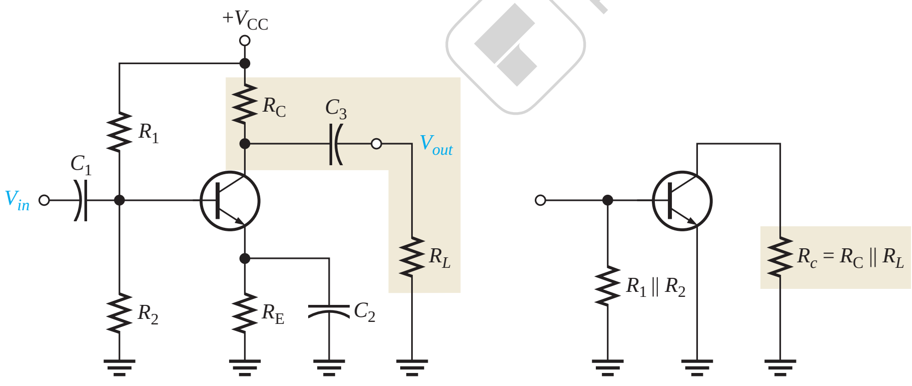
Effect of a Load on the Voltage Gain A **load** is the amount of current drawn from the output of an amplifier or other circuit through a load resistance. When a resistor, R_L, is connected to the output through the coupling capacitor C_3, as shown in Figure 6–17(a), it creates a load on the circuit. The collector resistance at the signal frequency is effectively R_C in parallel with R_L. Remember, the upper end of R_C is effectively at ac ground. The ac equivalent circuit is shown in Figure 6–17(b). The total ac collector resistance is

$$R_c = \frac{R_C R_L}{R_C + R_L}$$

Replacing R_C with R_c in the voltage gain expression gives

$$\mathbf{A_v = \frac{R_c}{r'_e}}$$ **Equation 6–7**

When $R_c < R_C$ because of R_L, the voltage gain is reduced. However, if $R_L \gg R_C$, then $R_c \cong R_C$ and the load has very little effect on the gain.



(a) Complete amplifier (b) AC equivalent ($X_{C1} = X_{C2} = X_{C3} = 0$)

▲ **FIGURE 6–17**

A common-emitter amplifier with an ac (capacitively) coupled load.

EXAMPLE 6–6 Calculate the base-to-collector voltage gain of the amplifier in Figure 6–16 when a load resistance of $5\text{ k}\Omega$ is connected to the output. The emitter is effectively bypassed and $r'_e = 6.58\ \Omega$.

Solution The ac collector resistance is

$$R_c = \frac{R_C R_L}{R_C + R_L} = \frac{(1.0\text{ k}\Omega)(5\text{ k}\Omega)}{6\text{ k}\Omega} = 833\ \Omega$$

Therefore,

$$A_v = \frac{R_c}{r'_e} = \frac{833\ \Omega}{6.58\ \Omega} = \mathbf{127}$$

The unloaded gain was found to be 152 in Example 6–5.

Related Problem Determine the base-to-collector voltage gain in Figure 6–16 when a 10 kΩ load resistance is connected from collector to ground. Change the resistance values as follows: $R_C = 1.8\ \text{k}\Omega$, $R_E = 1.0\ \text{k}\Omega$, $R_1 = 33\ \text{k}\Omega$, and $R_2 = 6.8\ \text{k}\Omega$. The emitter resistor is effectively bypassed and $r'_e = 18.5\ \Omega$.

Stability of the Voltage Gain

Stability is a measure of how well an amplifier maintains its design values over changes in temperature or for a transistor with a different β. Although bypassing R_E does produce the maximum voltage gain, there is a stability problem because the ac voltage gain is dependent on r'_e since $A_v = R_C/r'_e$. Also, r'_e depends on I_E and on temperature. This causes the gain to be unstable over changes in temperature because when r'_e increases, the gain decreases and vice versa.

With no bypass capacitor, the gain is decreased because R_E is now in the ac circuit ($A_v = R_C/(r'_e + R_E)$). However, with R_E unbypassed, the gain is much less dependent on r'_e. If $R_E \gg r'_e$, the gain is essentially independent of r'_e because

$$A_v \cong \frac{R_C}{R_E}$$

Swamping r'_e to Stabilize the Voltage Gain *Swamping* is a method used to minimize the effect of r'_e without reducing the voltage gain to its minimum value. This method "swamps" out the effect of r'_e on the voltage gain. Swamping is, in effect, a compromise between having a bypass capacitor across R_E and having no bypass capacitor at all.

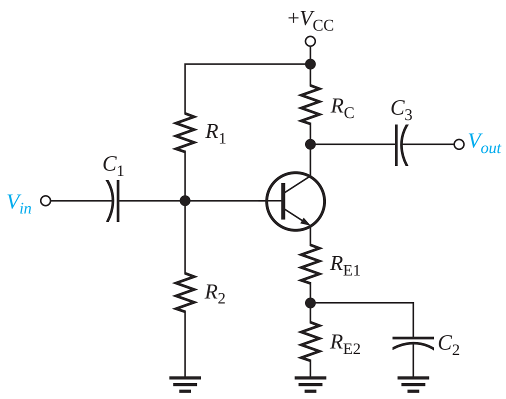
In a swamped amplifier, R_E is partially bypassed so that a reasonable gain can be achieved, and the effect of r'_e on the gain is greatly reduced or eliminated. The total external emitter resistance, R_E, is formed with two separate emitter resistors, R_{E1} and R_{E2}, as indicated in Figure 6–18. One of the resistors, R_{E2}, is bypassed and the other is not.

Both resistors ($R_{E1} + R_{E2}$) affect the dc bias while only R_{E1} affects the ac voltage gain.

$$A_v = \frac{R_C}{r'_e + R_{E1}}$$

▶ FIGURE 6–18

A swamped amplifier uses a partially bypassed emitter resistance to minimize the effect of r'_e on the gain in order to achieve gain stability.



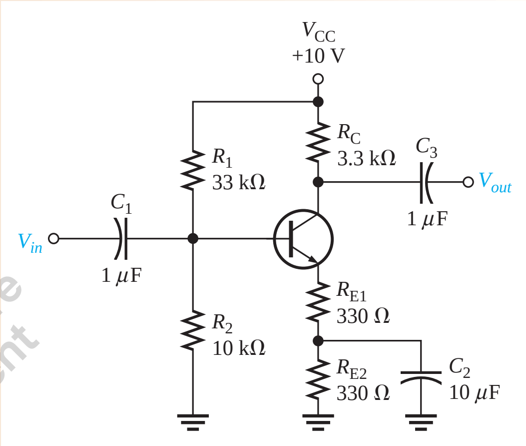
If R_{E1} is at least ten times larger than r'_e, then the effect of r'_e is minimized and the approximate voltage gain for the swamped amplifier is

$$A_v \cong \frac{R_C}{R_{E1}}$$ **Equation 6–8**

EXAMPLE 6–7

Determine the voltage gain of the swamped amplifier in Figure 6–19. Assume that the bypass capacitor has a negligible reactance for the frequency at which the amplifier is operated. Assume $r'_e = 20\ \Omega$.

▶ **FIGURE 6–19**



Solution R_{E2} is bypassed by C_2. R_{E1} is more than ten times r'_e so the approximate voltage gain is

$$A_v \cong \frac{R_C}{R_{E1}} = \frac{3.3\ \text{k}\Omega}{330\ \Omega} = \mathbf{10}$$

Related Problem What would be the voltage gain without C_2? What would be the voltage gain with C_2 bypassing both R_{E1} and R_{E2}?

The Effect of Swamping on the Amplifier's Input Resistance The ac input resistance, looking in at the base of a common-emitter amplifier with R_E completely bypassed, is $R_{in} = \beta_{ac} r'_e$. When the emitter resistance is partially bypassed, the portion of the resistance that is unbypassed is seen by the ac signal and results in an increase in the ac input resistance by appearing in series with r'_e. The formula is

$$R_{in(base)} = \beta_{ac}(r'_e + R_{E1})$$ **Equation 6–9**

EXAMPLE 6–8

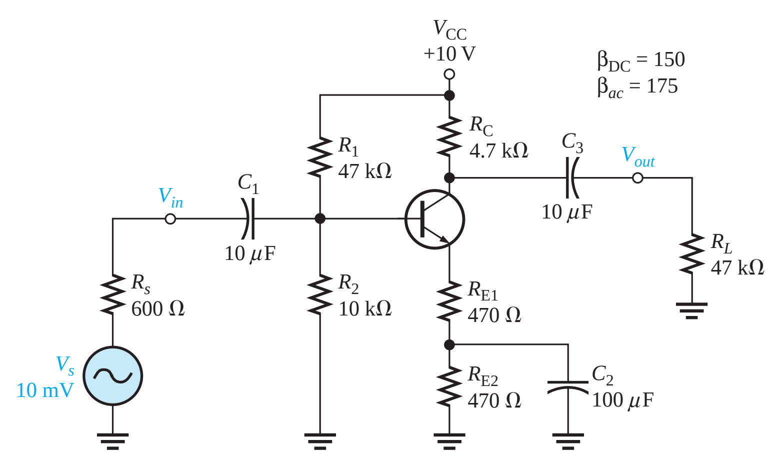
For the amplifier in Figure 6–20,

(a) Determine the dc collector voltage.

(b) Determine the ac collector voltage.

(c) Draw the total collector voltage waveform and the total output voltage waveform.

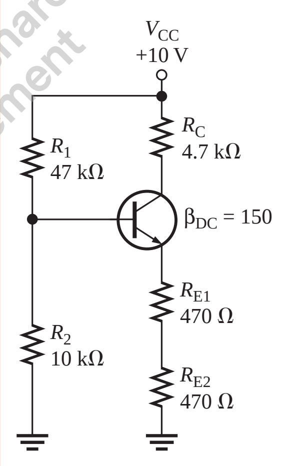
▶ FIGURE 6–20



Solution **(a)** Determine the dc bias values using the dc equivalent circuit in Figure 6–21.

▶ FIGURE 6–21

DC equivalent for the circuit in Figure 6–20.



Apply Thevenin's theorem and Kirchhoff's voltage law to the base-emitter circuit in Figure 6–21.

$$R_{TH} = \frac{R_1 R_2}{R_1 + R_2} = \frac{(47\text{ k}\Omega)(10\text{ k}\Omega)}{47\text{ k}\Omega + 10\text{ k}\Omega} = 8.25\text{ k}\Omega$$

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\frac{10\text{ k}\Omega}{47\text{ k}\Omega + 10\text{ k}\Omega}\right)10\text{ V} = 1.75\text{ V}$$

$$I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}} = \frac{1.75\text{ V} - 0.7\text{ V}}{940\ \Omega + 55\ \Omega} = 1.06\text{ mA}$$

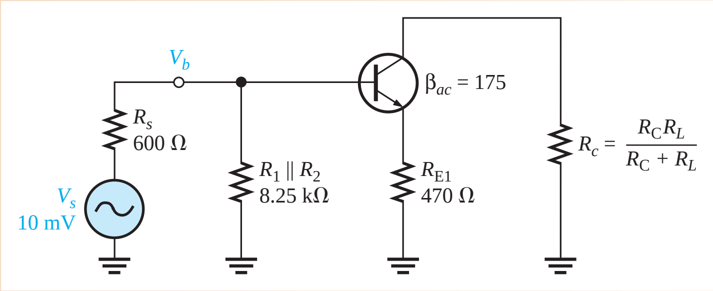
$$I_C \cong I_E = 1.06\text{ mA}$$

$$V_E = I_E(R_{E1} + R_{E2}) = (1.06\text{ mA})(940\ \Omega) = 1\text{ V}$$

$$V_B = V_E + 0.7\text{ V} = 1\text{ V} - 0.7\text{ V} = 0.3\text{ V}$$

$$V_C = V_{CC} - I_C R_C = 10\text{ V} - (1.06\text{ mA})(4.7\text{ k}\Omega) = \mathbf{5.02\text{ V}}$$

(b) The ac analysis is based on the ac equivalent circuit in Figure 6–22.



▶ FIGURE 6–22

AC equivalent for the circuit in Figure 6–20.

The first thing to do in the ac analysis is calculate r'_e.

$$r'_e \cong \frac{25\text{ mV}}{I_E} = \frac{25\text{ mV}}{1.06\text{ mA}} = 23.6\ \Omega$$

Next, determine the attenuation in the base circuit. Looking from the 600 Ω source, the total R_{in} is

$$R_{in(tot)} = R_1 \parallel R_2 \parallel R_{in(base)}$$
$$R_{in(base)} = \beta_{ac}(r'_e + R_{E1}) = 175(494\ \Omega) = 86.5\text{ k}\Omega$$

Therefore,

$$R_{in(tot)} = 47\text{ k}\Omega \parallel 10\text{ k}\Omega \parallel 86.5\text{ k}\Omega = 7.53\text{ k}\Omega$$

The attenuation from source to base is

$$\text{Attenuation} = \frac{V_s}{V_b} = \frac{R_s + R_{in(tot)}}{R_{in(tot)}} = \frac{600\ \Omega + 7.53\text{ k}\Omega}{7.53\text{ k}\Omega} = 1.08$$

Before A_v can be determined, you must know the ac collector resistance R_c.

$$R_c = \frac{R_C R_L}{R_C + R_L} = \frac{(4.7\text{ k}\Omega)(47\text{ k}\Omega)}{4.7\text{ k}\Omega + 47\text{ k}\Omega} = 4.27\text{ k}\Omega$$

The voltage gain from base to collector is

$$A_v \cong \frac{R_c}{R_{E1}} = \frac{4.27\text{ k}\Omega}{470\ \Omega} = 9.09$$

The overall voltage gain is the reciprocal of the attenuation times the amplifier voltage gain.

$$A'_v = \left(\frac{V_b}{V_s}\right)A_v = (0.93)(9.09) = 8.45$$

The source produces 10 mV rms, so the rms voltage at the collector is

$$V_c = A'_v V_s = (8.45)(10\text{ mV}) = \mathbf{84.5\text{ mV}}$$

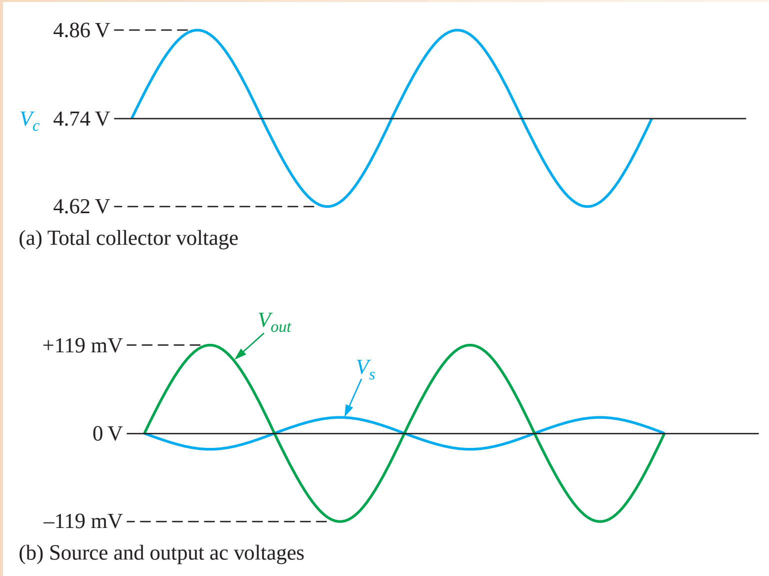
(c) The total collector voltage is the signal voltage of 84.5 mV rms riding on a dc level of 4.74 V, as shown in Figure 6–23(a), where approximate peak values are determined as follows:

$$\text{Max } V_{c(p)} = V_C + 1.414\,V_c = 4.74\text{ V} + (84.5\text{ mV})(1.414) = 4.86\text{ V}$$
$$\text{Min } V_{c(p)} = V_C - 1.414\,V_c = 4.74\text{ V} - (84.5\text{ mV})(1.414) = 4.62\text{ V}$$

The coupling capacitor, C_3, keeps the dc level from getting to the output. So, V_{out} is equal to the ac component of the collector voltage ($V_{out(p)} = (84.5\text{ mV})(1.414) = 119\text{ mV}$),

▶ FIGURE 6–23

Voltages for Figure 6–20.



as indicated in Figure 6–23(b). The source voltage, V_s, is shown to emphasize the phase inversion.

Related Problem What is A_v in Figure 6–20 with R_L removed?

Open the Multisim file E06-08 in the Examples folder on the companion website. Measure the dc and the ac values of the collector voltage and compare with the calculated values.

Current Gain

The current gain from base to collector is I_c/I_b or β_{ac}. However, the overall current gain of the common-emitter amplifier is

Equation 6–10

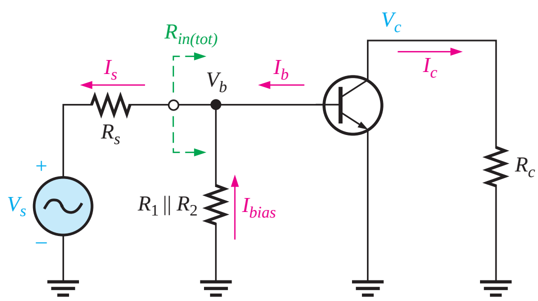
$$A_i = \frac{I_c}{I_s}$$

I_s is the total signal input current produced by the source, part of which (I_b) is base current and part of which (I_{bias}) goes through the bias circuit ($R_1 \| R_2$), as shown in Figure 6–24. The source "sees" a total resistance of $R_s + R_{in(tot)}$. The total current produced by the source is

$$I_s = \frac{V_s}{R_s + R_{in(tot)}}$$

▶ FIGURE 6–24

Signal currents (directions shown are for the positive half-cycle of V_s).



Power Gain

The overall power gain is the product of the overall voltage gain (A'_v) and the overall current gain (A_i).

$$A_p = A'_v A_i$$

Equation 6–11

where $A'_v = V_c/V_s$.

SECTION 6–3 CHECKUP

1. In the dc equivalent circuit of an amplifier, how are the capacitors treated?
2. When the emitter resistor is bypassed with a capacitor, how is the gain of the amplifier affected?
3. Explain swamping.
4. List the elements included in the total input resistance of a common-emitter amplifier.
5. What elements determine the overall voltage gain of a common-emitter amplifier?
6. When a load resistor is capacitively coupled to the collector of a CE amplifier, is the voltage gain increased or decreased?
7. What is the phase relationship of the input and output voltages of a CE amplifier?

6–4 THE COMMON-COLLECTOR AMPLIFIER

The **common-collector** (CC) amplifier is usually referred to as an emitter-follower (EF). The input is applied to the base through a coupling capacitor, and the output is at the emitter. The voltage gain of a CC amplifier is approximately 1, and its main advantages are its high input resistance and current gain.

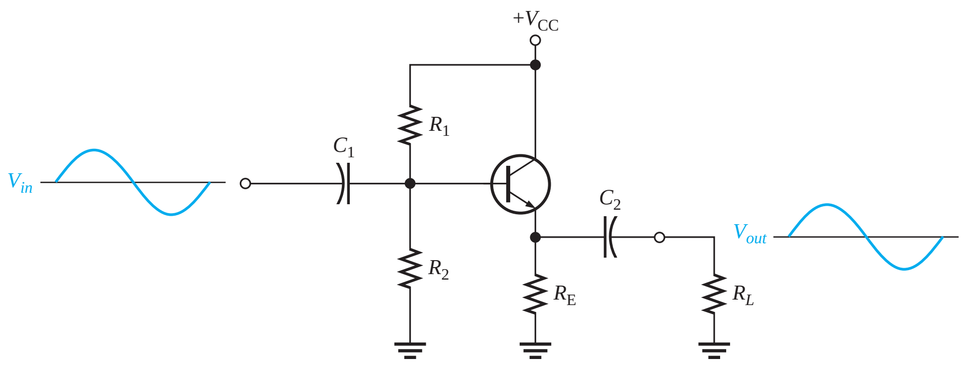
After completing this section, you should be able to

- **Describe and analyze the operation of common-collector amplifiers**
- Discuss the emitter-follower amplifier with voltage-divider bias
- Analyze the amplifier for voltage gain
  - Explain the term *emitter-follower*
- Discuss and calculate input resistance
- Determine output resistance
- Determine current gain
- Determine power gain
- Describe the Darlington pair
  - Discuss an application
- Discuss the Sziklai pair

An **emitter-follower** circuit with voltage-divider bias is shown in Figure 6–25. Notice that the input signal is capacitively coupled to the base, the output signal is capacitively coupled from the emitter, and the collector is at ac ground. There is no phase inversion, and the output is approximately the same amplitude as the input.

▶ FIGURE 6–25

Emitter-follower with voltage-divider bias.



Voltage Gain

As in all amplifiers, the voltage gain is $A_v = V_{out}/V_{in}$. The capacitive reactances are assumed to be negligible at the frequency of operation. For the emitter-follower, as shown in the ac model in Figure 6–26,

$$V_{out} = I_eR_e$$

and

$$V_{in} = I_e(r'_e + R_e)$$

Therefore, the voltage gain is

$$A_v = \frac{I_eR_e}{I_e(r'_e + R_e)}$$

The I_e current terms cancel, and the base-to-emitter voltage gain expression simplifies to

$$A_v = \frac{R_e}{r'_e + R_e}$$

where R_e is the parallel combination of R_E and R_L. If there is no load, then $R_e = R_E$. Notice that the gain is always less than 1. If $R_e \gg r'_e$, then a good approximation is

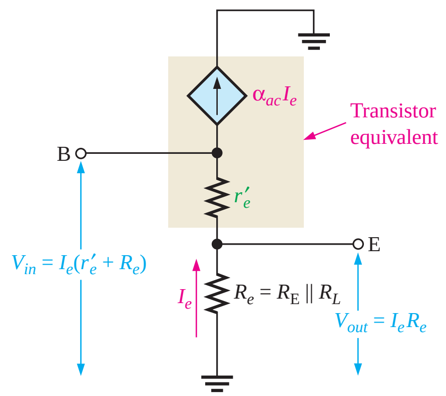
Equation 6–12

$$\mathbf{A_v \cong 1}$$

Since the output voltage is at the emitter, it is in phase with the base voltage, so there is no inversion from input to output. Because there is no inversion and because the voltage gain is approximately 1, the output voltage closely follows the input voltage in both phase and amplitude; thus the term *emitter-follower.*

▶ FIGURE 6–26

Emitter-follower model for voltage gain derivation.



Input Resistance

The emitter-follower is characterized by a high input resistance; this is what makes it a useful circuit. Because of the high input resistance, it can be used as a buffer to minimize loading effects when a circuit is driving a low-resistance load. The derivation of the input resistance, looking in at the base of the common-collector amplifier, is similar to that for the common-emitter amplifier. In a common-collector circuit, however, the emitter resistor is *never* bypassed because the output is taken across R_e, which is R_E in parallel with R_L.

$$R_{in(base)} = \frac{V_{in}}{I_{in}} = \frac{V_b}{I_b} = \frac{I_e(r'_e + R_e)}{I_b}$$

Since $I_e \cong I_c = \beta_{ac}I_b$,

$$R_{in(base)} \cong \frac{\beta_{ac}I_b(r'_e + R_e)}{I_b}$$

The I_b terms cancel; therefore,

$$R_{in(base)} \cong \beta_{ac}(r'_e + R_e)$$

If $R_e \gg r'_e$, then the input resistance at the base is simplified to

$$\boldsymbol{R_{in(base)} \cong \beta_{ac}R_e}$$ **Equation 6–13**

The bias resistors in Figure 6–25 appear in parallel with $R_{in(base)}$, looking from the input source; and just as in the common-emitter circuit, the total input resistance is

$$R_{in(tot)} = R_1 \parallel R_2 \parallel R_{in(base)}$$

Output Resistance

With the load removed, the output resistance, looking into the emitter of the emitter-follower, is approximated as follows:

$$\boldsymbol{R_{out} \cong \left(\frac{R_s}{\beta_{ac}}\right) \parallel R_E}$$ **Equation 6–14**

R_s is the resistance of the input source. The derivation of Equation 6–14, found in "Derivations of Selected Equations" at www.pearsonhighered.com/floyd, is relatively involved and several assumptions have been made. The output resistance is very low, making the emitter-follower useful for driving low-resistance loads.

Current Gain

The current gain for the emitter-follower in Figure 6–25 is

$$\boldsymbol{A_i = \frac{I_e}{I_{in}}}$$ **Equation 6–15**

where $I_{in} = V_{in}/R_{in(tot)}$.

Power Gain

The common-collector power gain is the product of the voltage gain and the current gain. For the emitter-follower, the power gain is approximately equal to the current gain because the voltage gain is approximately 1.

$$A_p = A_v A_i$$

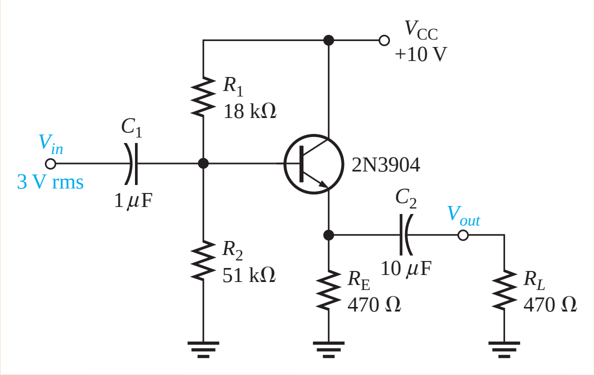
Since $A_v \cong 1$, the power gain is

$$\boldsymbol{A_p \cong A_i}$$ **Equation 6–16**

EXAMPLE 6–9

Determine the total input resistance of the emitter-follower in Figure 6–27. Also find the voltage gain, current gain, and power gain in terms of power delivered to the load, R_L. Assume $\beta_{ac} = 175$ and that the capacitive reactances are negligible at the frequency of operation.

▶ **FIGURE 6–27**



Solution The ac emitter resistance external to the transistor is

$$R_e = R_E \| R_L = 470\ \Omega \| 470\ \Omega = 235\ \Omega$$

The approximate resistance, looking in at the base, is

$$R_{in(base)} \cong \beta_{ac} R_e = (175)(235\ \Omega) = 41.1\ \text{k}\Omega$$

The total input resistance is

$$R_{in(tot)} = R_1 \| R_2 \| R_{in(base)} = 18\ \text{k}\Omega \| 51\ \text{k}\Omega \| 41.1\ \text{k}\Omega = \mathbf{10.1\ k\Omega}$$

The voltage gain is $A_v \cong 1$. By using r'_e, you can determine a more precise value of A_v if necessary.

$$V_E = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} - V_{BE} = \left(\frac{51\ \text{k}\Omega}{18\ \text{k}\Omega + 51\ \text{k}\Omega}\right)10\ \text{V} - 0.7\ \text{V}$$
$$= (0.739)(10\ \text{V}) - 0.7\ \text{V} = 6.69\ \text{V}$$

Therefore,

$$I_E = \frac{V_E}{R_E} = \frac{6.69\ \text{V}}{470\ \Omega} = 14.2\ \text{mA}$$

and

$$r'_e \cong \frac{25\ \text{mV}}{I_E} = \frac{25\ \text{mV}}{14.2\ \text{mA}} = 1.76\ \Omega$$

So,

$$A_v = \frac{R_e}{r'_e + R_e} = \frac{235\ \Omega}{237\ \Omega} = \mathbf{0.992}$$

The small difference in A_v as a result of considering r'_e is insignificant in most cases.

The current gain is $A_i = I_e/I_{in}$. The calculations are as follows:

$$I_e = \frac{V_e}{R_e} = \frac{A_v V_b}{R_e} \cong \frac{(0.992)(3\ \text{V})}{235\ \Omega} = \frac{2.98\ \text{V}}{235\ \Omega} = 12.7\ \text{mA}$$

$$I_{in} = \frac{V_{in}}{R_{in(tot)}} = \frac{3\ \text{V}}{10.1\ \text{k}\Omega} = 297\ \mu\text{A}$$

$$A_i = \frac{I_e}{I_{in}} = \frac{12.7\ \text{mA}}{297\ \mu\text{A}} = \mathbf{42.8}$$

The power gain is

$$A_p \cong A_i = 42.8$$

Since $R_L = R_E$, one-half of the power is dissipated in R_E and one-half in R_L. Therefore, in terms of power to the load, the power gain is

$$A_{p(load)} = \frac{A_p}{2} = \frac{42.8}{2} = \mathbf{21.4}$$

Related Problem If R_L in Figure 6–27 is decreased in value, does power gain to the load increase or decrease?

Open the Multisim file E06-09 in the Examples folder on the companion website. Measure the voltage gain and compare with the calculated value.

The Darlington Pair

As you have seen, β_{ac} is a major factor in determining the input resistance of an amplifier. The β_{ac} of the transistor limits the maximum achievable input resistance you can get from a given emitter-follower circuit.

One way to boost input resistance is to use a **Darlington pair,** as shown in Figure 6–28. The collectors of two transistors are connected, and the emitter of the first drives the base of the second. This configuration achieves β_{ac} multiplication as shown in the following steps. The emitter current of the first transistor is

$$I_{e1} \cong \beta_{ac1} I_{b1}$$

This emitter current becomes the base current for the second transistor, producing a second emitter current of

$$I_{e2} \cong \beta_{ac2} I_{e1} = \beta_{ac1}\beta_{ac2} I_{b1}$$

Therefore, the effective current gain of the Darlington pair is

$$\beta_{ac} = \beta_{ac1}\beta_{ac2}$$

Neglecting r'_e by assuming that it is much smaller than R_E, the input resistance is

$$\boldsymbol{R_{in} = \beta_{ac1}\beta_{ac2} R_E} \quad \text{Equation 6–17}$$

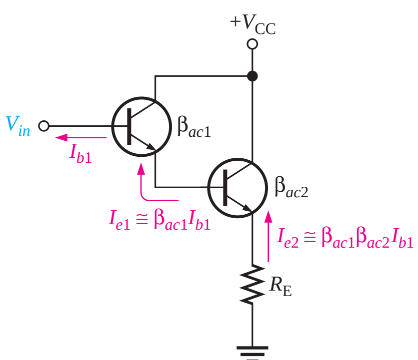


FIGURE 6–28

A Darlington pair multiplies $\boldsymbol{\beta_{ac}}$.

An Application The emitter-follower is often used as an interface between a circuit with a high output resistance and a low-resistance load. In such an application, the emitter-follower is called a *buffer.*

HISTORY NOTE

Sidney Darlington (1906–1997) was a renowned electrical engineer, whose name lives on through the transistor configuration he patented in 1953. He also had inventions in chirp radar, bombsights, and gun and rocket guidance. In 1945, he was awarded the Presidential Medal of Freedom and in 1975, he received IEEE's Edison Medal "for basic contributions to network theory and for important inventions in radar systems and electronic circuits" and the IEEE Medal of Honor in 1981 "for fundamental contributions to filtering and signal processing leading to chirp radar."

known as a *complementary Darlington* or a *compound transistor.* The current gain is about the same as in the Darlington pair, as illustrated. The difference is that the Q_2 base current is the Q_1 collector current instead of emitter current, as in the Darlington arrangement.

An advantage of the Sziklai pair, compared to the Darlington, is that it takes less voltage to turn it on because only one barrier potential has to be overcome. A Sziklai pair is sometimes used in conjunction with a Darlington pair as the output stage of power amplifiers. In this case, the output power transistors are both the same type (two *npn* or two *pnp* transistors). This makes it easier to obtain exact matches of the output transistors, resulting in improved thermal stability and better sound quality in audio applications.

SECTION 6–4 CHECKUP

1. What is a common-collector amplifier called?
2. What is the ideal maximum voltage gain of a common-collector amplifier?
3. What characteristic of the common-collector amplifier makes it a useful circuit?

6–5 THE COMMON-BASE AMPLIFIER

The common-base (CB) amplifier provides high voltage gain with a maximum current gain of 1. Since it has a low input resistance, the CB amplifier is the most appropriate type for certain applications where sources tend to have very low-resistance outputs.

After completing this section, you should be able to

- **Describe and analyze the operation of common-base amplifiers**
- Determine the voltage gain
  - Explain why there is no phase inversion
- Discuss and calculate input resistance
- Determine output resistance
- Determine current gain
- Determine power gain

A typical **common-base** amplifier is shown in Figure 6–31. The base is the common terminal and is at ac ground because of capacitor C_2. The input signal is capacitively coupled to the emitter. The output is capacitively coupled from the collector to a load resistor.

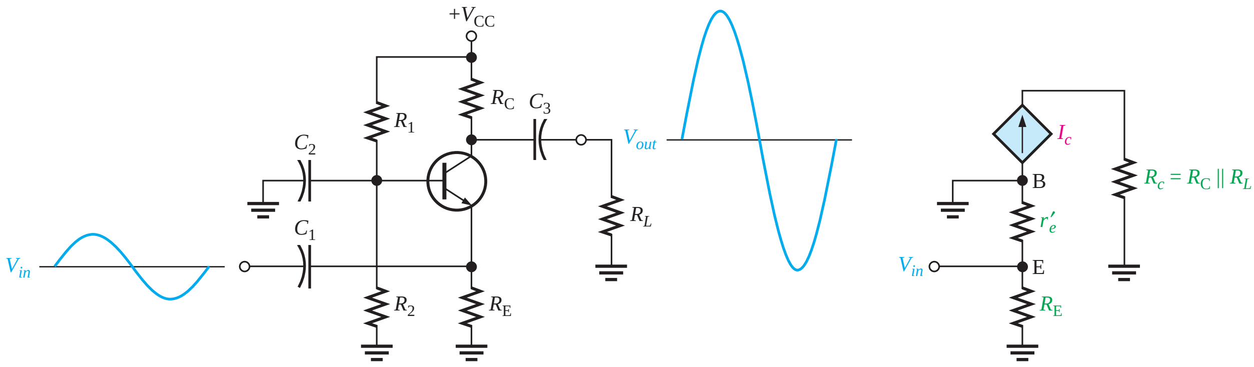
FYI

The CB amplifier is useful at high frequencies when impedance matching is required because input impedance can be controlled and because noninverting amps have better frequency response.

Voltage Gain

The voltage gain from emitter to collector is developed as follows ($V_{in} = V_e, V_{out} = V_c$).

$$A_v = \frac{V_{out}}{V_{in}} = \frac{V_c}{V_e} = \frac{I_c R_c}{I_e(r'_e \parallel R_E)} \cong \frac{I_e R_c}{I_e(r'_e \parallel R_E)}$$



(a) Complete circuit with load

(b) AC equivalent model

▲ FIGURE 6–31

Common-base amplifier with voltage-divider bias.

If $R_E \gg r'_e$, then

$$A_v \cong \frac{R_c}{r'_e}$$ **Equation 6–18**

where $R_c = R_C \| R_L$. Notice that the gain expression is the same as for the common-emitter amplifier. However, there is no phase inversion from emitter to collector.

Input Resistance

The resistance, looking in at the emitter, is

$$R_{in(emitter)} = \frac{V_{in}}{I_{in}} = \frac{V_e}{I_e} = \frac{I_e(r'_e \| R_E)}{I_e}$$

If $R_E \gg r'_e$, then

$$R_{in(emitter)} \cong r'_e$$ **Equation 6–19**

R_E is typically much greater than r'_e, so the assumption that $r'_e \| R_E \cong r'_e$ is usually valid. The input resistance can be set to a desired value by using a swamping resistor.

Output Resistance

Looking into the collector, the ac collector resistance, r'_c, appears in parallel with R_C. As you have previously seen in connection with the CE amplifier, r'_c is typically much larger than R_C, so a good approximation for the output resistance is

$$R_{out} \cong R_C$$ **Equation 6–20**

Current Gain

The current gain is the output current divided by the input current. I_c is the ac output current, and I_e is the ac input current. Since $I_c \cong I_e$, the current gain is approximately 1.

$$A_i \cong 1$$ **Equation 6–21**

Power Gain

Since the current gain is approximately 1 for the common-base amplifier and $A_p = A_v A_i$, the power gain is approximately equal to the voltage gain.

$$A_p \cong A_v$$ **Equation 6–22**