1

SEMICONDUCTOR BASICS

INTRODUCTION

Electronic devices such as diodes, transistors, and integrated circuits are made of a semiconductive material. To properly 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 diode and certain types of transistors.

CHAPTER OUTLINE

CHAPTER OBJECTIVES

- Discuss the basic structure of atoms
- Discuss semiconductors, conductors, and insulators and how they basically differ
- Discuss covalent bonding in silicon
- Describe how current is produced in a semiconductor
- Describe the properties of *n*-type and *p*-type semiconductors
- Describe a diode and how a *pn* junction is formed
- Discuss the bias of a diode
- Analyze the voltage–current (*V–I*) characteristic curve of a diode
- Discuss the operation of diodes and explain the three diode models
- Test a diode using a digital multimeter

KEY TERMS

Atom
Proton
Electron
Shells
Valance
Ionization
Free electron
Conductor
Insulator
Semiconductor
Silicon
Crystal
Hole
Doping
Diode
PN junction
Barrier potential
Bias
Forward bias
Reverse bias
V–I characteristic
Cathode
Anode

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1–1 ATOMIC STRUCTURE

All matter is made of atoms; and all atoms consist of electrons, protons, and neutrons. In this section, you will learn about the structure of the atom, electron orbits and shells, valence electrons, ions, and two semiconductive materials—silicon and germanium. Semiconductive material is important because the configuration of certain electrons in an atom is the key factor in determining how a given material conducts electrical current.

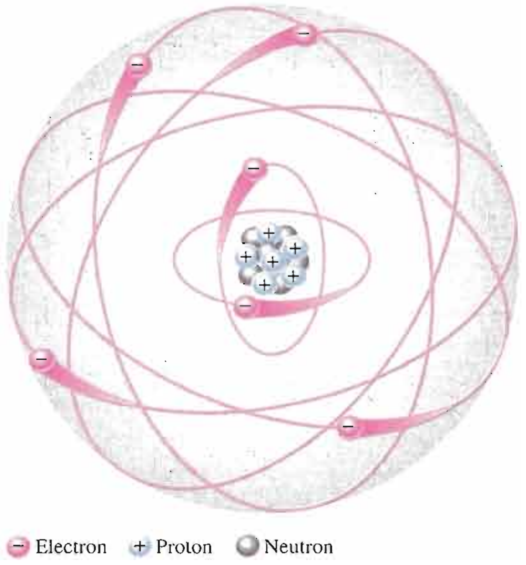
After completing this section, you should be able to

- **Discuss the basic structure of atoms**
- Define *nucleus, proton, neutron*, and *electron*
- Describe an element's atomic number
- Explain electron shells
- Describe a valence electron
- Describe ionization
- Describe a free electron

An **atom*** is the smallest particle of an element that retains the characteristics of that element. Each of the known 109 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**.

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.



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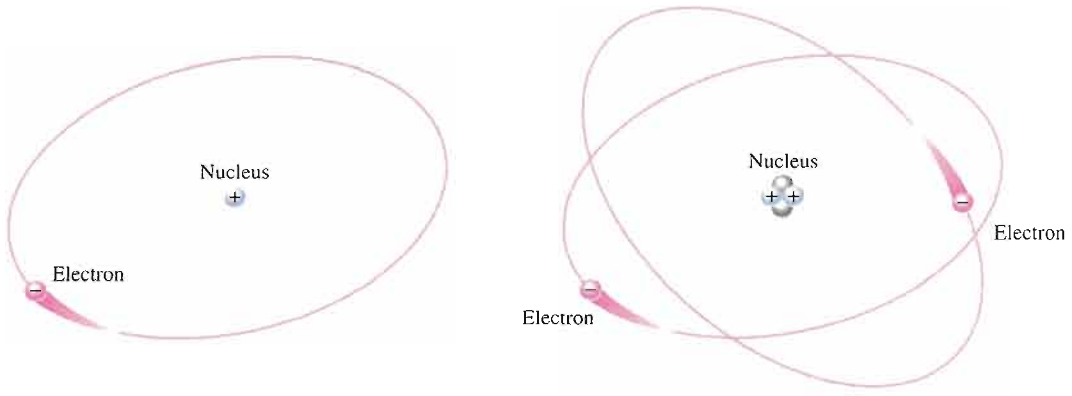
*All bold terms are in the end-of-book glossary. The bold terms in color are key terms and are also defined at the end of the chapter.

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.



(a) Hydrogen atom

(b) Helium atom

▲ FIGURE 1–2

Two simple atoms, hydrogen and helium.

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.

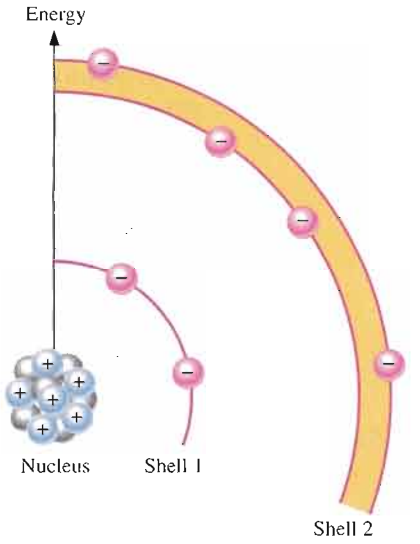
Electron Shells and Orbits

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. It is known that only discrete (separate and distinct) values of electron energies exist within atomic structures. Therefore, electrons must orbit only at discrete distances from the nucleus.

Energy Levels Each discrete distance (**orbit**) from the nucleus corresponds to a certain energy level. In an atom, the orbits are grouped into energy bands known as **shells**. A given atom has a fixed number of shells. Each shell has a fixed maximum number of electrons at permissible energy levels (orbits). The differences in energy levels within a shell are much smaller than the difference in energy between shells. The shells are designated 1, 2, 3, and so on, with 1 being closest to the nucleus. Some references designate shells by the letters *K, L, M*, and so on. This energy band concept is illustrated in Figure 1–3, which shows the 1st shell with one energy level and the 2nd shell with two energy levels. Additional shells may exist in other types of atoms, depending on the element.

FIGURE 1–3

Energy increases as the distance from the nucleus increases.



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.

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 orbits within the valence shell when external energy is absorbed.

If a valence electron acquires a sufficient amount of 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**. When a free electron loses energy and falls into the outer shell of a neutral hydrogen atom, the atom becomes negatively charged (more electrons than protons) and is called a *negative ion*, designated H^-.

The 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 innermost shell is number 1, the next shell is number 2, and so on. 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 the second shell is

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

The maximum number of electrons that can exist in the third shell is

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

The maximum number of electrons that can exist in the fourth shell is

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

All shells in a given atom must be completely filled with electrons except the outer (valence) shell.

SECTION 1–1 REVIEW

Answers are at the end of the chapter.

1. Describe an atom.
2. What is an electron?
3. What is a valence electron?
4. What is a free electron?
5. How are ions formed?

1–2 SEMICONDUCTORS, CONDUCTORS, AND INSULATORS

In terms of their electrical properties, materials can be classified into three groups: conductors, semiconductors, and insulators. In this section, we will examine the properties of semiconductors and compare them to conductors and insulators.

After completing this section, you should be able to

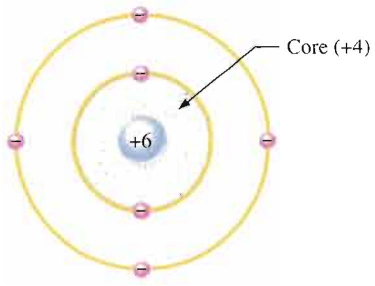
- **Discuss semiconductors, conductors, and insulators and how they basically differ**
- Define the core of an atom
- Describe the atomic structure of copper, silicon, germanium, and carbon
- List the four best conductors
- List four semiconductors
- Discuss the difference between conductors and semiconductors
- Discuss the difference between silicon and germanium semiconductors
- Explain why silicon is much more widely used than germanium

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 1–4 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).

▶ FIGURE 1–4

Diagram of a carbon atom.



Conductors

A **conductor** is a material that easily conducts electrical current. The best conductors are single-element materials, such as copper, silver, gold, and aluminum, which are characterized by atoms with only one valence electron very loosely bound to the atom. These loosely bound valence electrons can easily break away from their atoms and become free electrons. Therefore, a conductive material has many free electrons that, when moving in the same direction, make up the **current**.

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. Valence electrons are tightly bound to the atoms; therefore, there are very few free electrons in an insulator.

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. The most common single-element semiconductors are **silicon**, **germanium**, and **carbon**. Compound semiconductors such as gallium arsenide are also commonly used. The single-element semiconductors are characterized by atoms with four valence electrons.

Energy Bands

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*. 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 1–5 shows energy diagrams for insulators, semiconductors, and conductors. Notice in part (a) that insulators have a very wide energy gap. Valence electrons do not jump into the conduction band except under breakdown conditions where extremely high voltages are applied across the material. As you can see in part (b), semiconductors have a much narrower energy gap. This gap permits some valence electrons to jump into the conduction band and become free electrons. By contrast, as part (c) illustrates, the energy bands in conductors overlap. In a conductive material there is always a large number of free electrons.

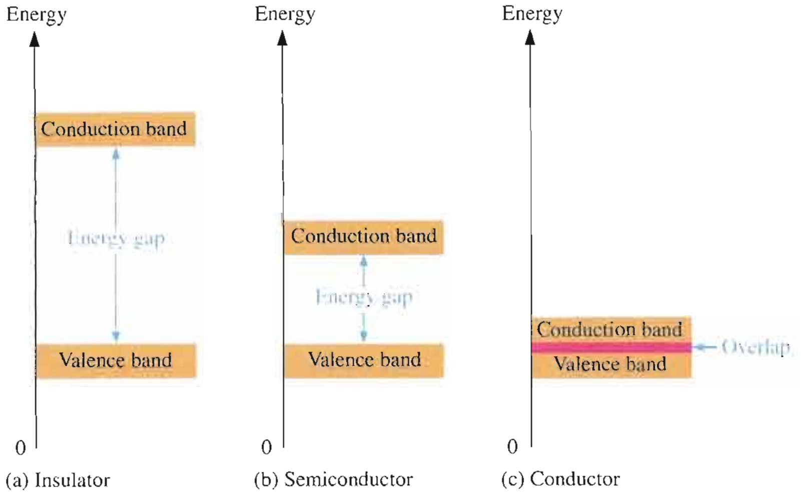
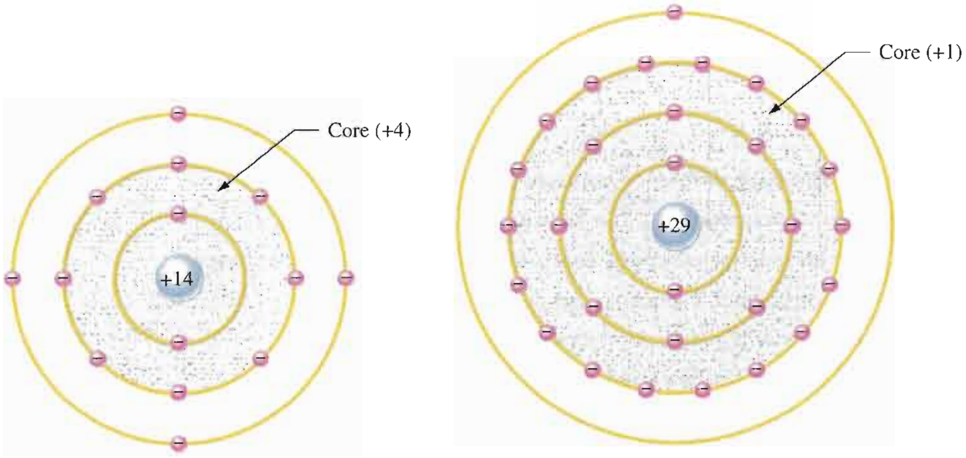


FIGURE 1–5

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. Diagrams of the silicon atom and the copper atom are shown in Figure 1–6. 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 is everything except the valence electrons.



(a) Silicon atom

(b) Copper atom

FIGURE 1–6

Diagrams of the silicon and copper atoms.

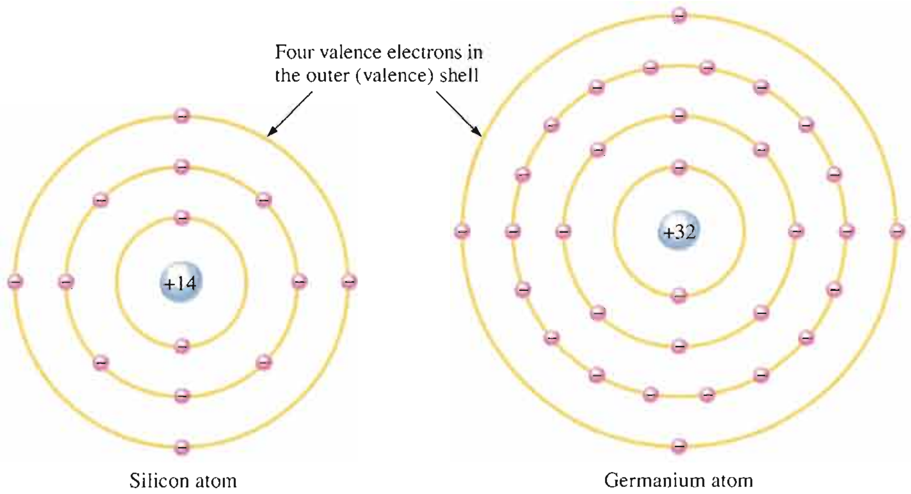
The valence electron in the copper atom "feels" an attractive force of +1 compared to a valence electron in the silicon atom which "feels" an attractive force of +4. Therefore, there is four times more force trying to hold a valence electron to the atom in silicon than in copper. The copper's valence 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 in the conduction band 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 1–7. **Silicon** is the most widely used material in diodes, transistors, integrated circuits, and other semiconductor devices. Notice that both silicon and germanium have the characteristic four valence electrons.

FIGURE 1–7

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 this is a basic reason why silicon is the most widely used semiconductive material.

SECTION 1–2 REVIEW

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?

1–3 COVALENT BONDS

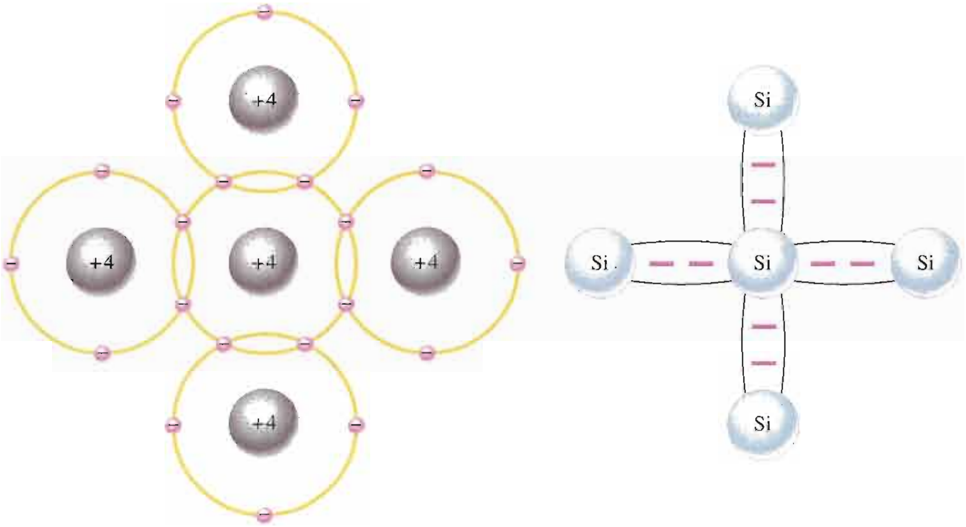
When atoms combine to form a solid, crystalline material, they arrange themselves in a symmetrical pattern. The atoms within the crystal structure are held together by covalent bonds, which are created by the interaction of the valence electrons of the atoms. Silicon is a crystalline material.

After completing this section, you should be able to

- **Discuss covalent bonding in silicon**

- Define a covalent bond
- Explain what a covalent bond consists of
- Explain how a silicon crystal is formed

Figure 1–8 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 1–9. An **intrinsic** crystal is one that has no impurities. Covalent bonding for germanium is similar because it also has four valence electrons.



(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 1–8

Illustration of covalent bonds in silicon.

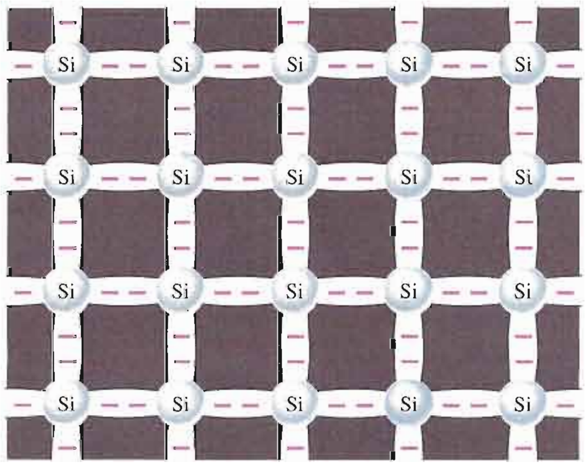


FIGURE 1–9

Covalent bonds in a silicon crystal.

SECTION 1–3 REVIEW

1. How are covalent bonds formed?
2. What is meant by the term *intrinsic*?
3. What is a crystal?
4. Effectively, how many valence electrons are there in each atom within a silicon crystal?

1–4 CONDUCTION 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 the basic current mechanisms. In this section, you will see how conduction occurs in semiconductive material.

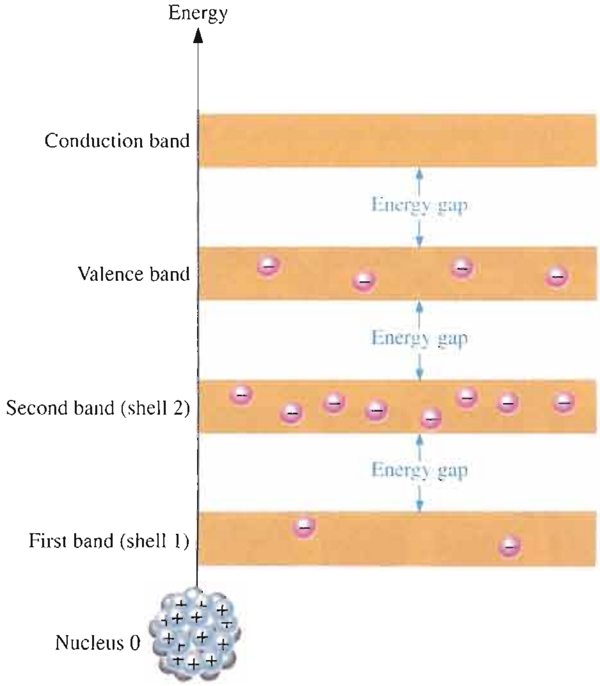
After completing this section, you should be able to

- **Describe how current is produced in a semiconductor**
- Describe a conduction electron
- Define *hole*
- Explain what an electron-hole pair is
- Discuss recombination
- Explain the difference between electron current 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 energy gaps, in which no electrons can exist. Figure 1–10 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.

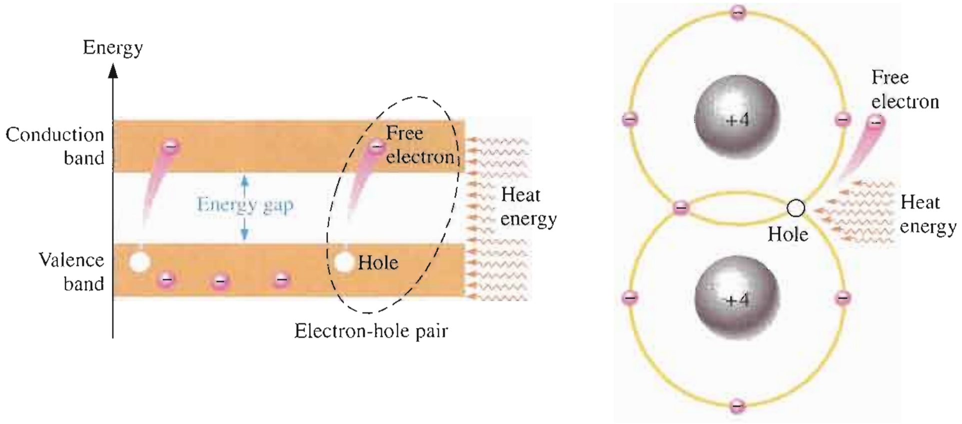
FIGURE 1–10

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 1–11(a) and in the bonding diagram of Figure 1–11(b).



(a) Energy diagram

(b) Bonding diagram

FIGURE 1–11

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

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 1–12.

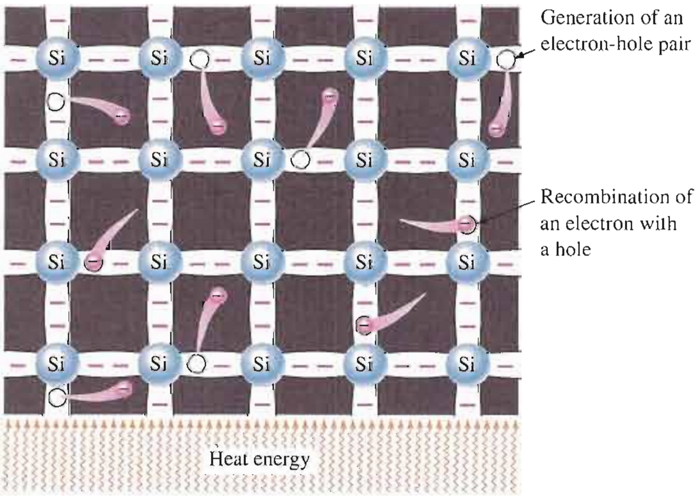


FIGURE 1–12

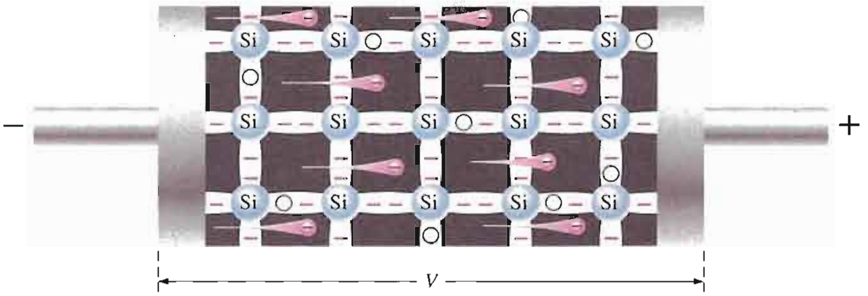
Electron-hole pairs in a silicon crystal. Free electrons are being generated continuously while some recombine with holes.

Electron and Hole Current

When a voltage is applied across a piece of intrinsic silicon, as shown in Figure 1–13, 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 1–13

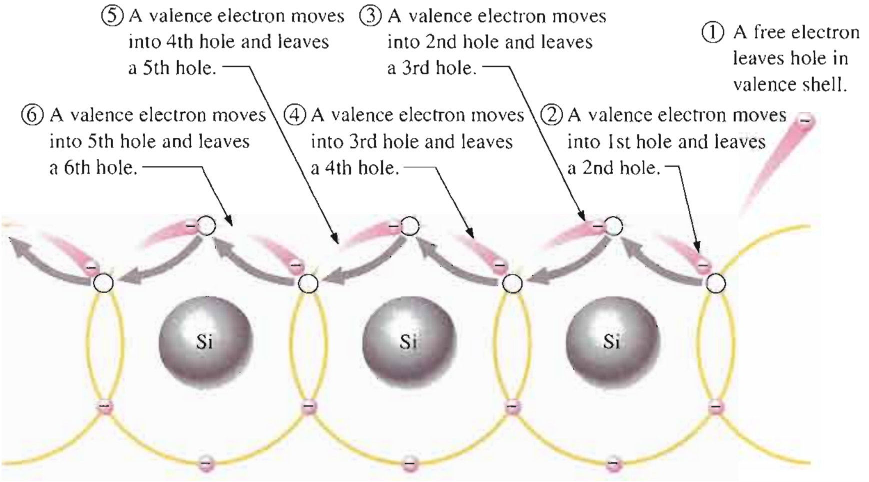
Electron current in intrinsic silicon is produced by the movement of thermally generated free electrons.



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 1–14. This is called *hole current.*

FIGURE 1–14

Hole current in intrinsic silicon.



⑤ A valence electron moves into 4th hole and leaves a 5th hole.

③ A valence electron moves into 2nd hole and leaves a 3rd hole.

① A free electron leaves hole in valence shell.

⑥ A valence electron moves into 5th hole and leaves a 6th hole.

④ A valence electron moves into 3rd hole and leaves a 4th hole.

② A valence electron moves into 1st hole and leaves a 2nd hole.

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 1–4 REVIEW

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

1–5 *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 as you will learn in this section. 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
- Explain how *p*-type semiconductors are formed
- Describe a majority carrier and minority carrier

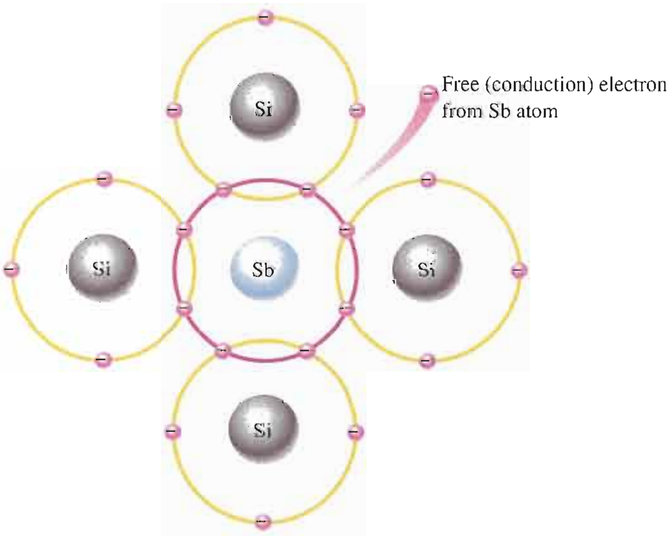
Doping

The conductivity of silicon and germanium 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 1–15, 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 attached to any atom. Because the pentavalent atom gives up an electron, it is often called a *donor atom*. The number of



◀ FIGURE 1–15

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.

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.

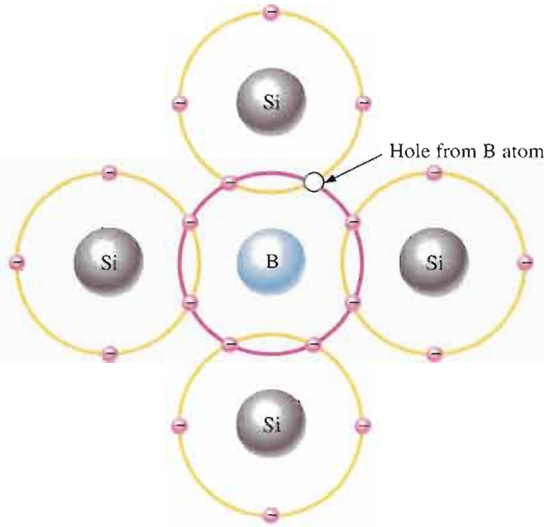
Majority and Minority Carriers Since most of the current carriers are electrons, silicon (or germanium) doped with pentavalent atoms is an *n*-type semiconductor (the *n* stands for the negative charge on an electron). The electrons are called the **majority carriers** in *n*-type material. Although 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 1–16, 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.

FIGURE 1–16

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



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. Holes can be thought of as positive charges because the absence of an electron leaves a net positive charge on the atom. 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 free electrons that are created when electron-hole pairs are thermally generated. These free electrons are *not* produced by the addition of the trivalent impurity atoms. Electrons in *p*-type material are the minority carriers.

SECTION 1–5 REVIEW

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

1–6 THE DIODE

If 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 and a basic diode is created. A **diode** is a device that conducts current in only one direction. The *pn* junction is the feature that allows diodes, certain transistors, and other devices to work.

After completing this section, you should be able to

- **Describe a diode and 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

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.

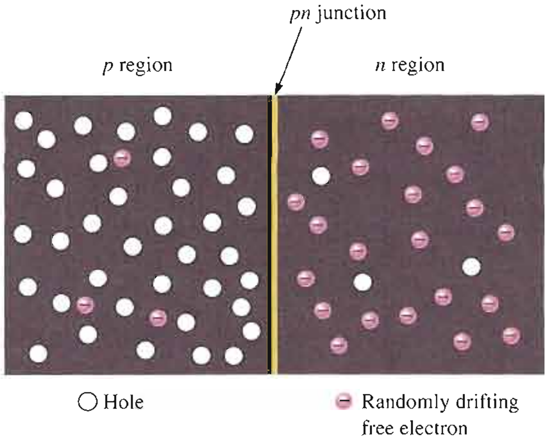
If a piece of intrinsic silicon is doped so that part is *n*-type and the other part is *p*-type, a ***pn* junction** forms at the boundary between the two regions and a diode is created, as indicated in Figure 1–17. The *p* region has many holes (majority carriers) from the impurity atoms and only a 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).

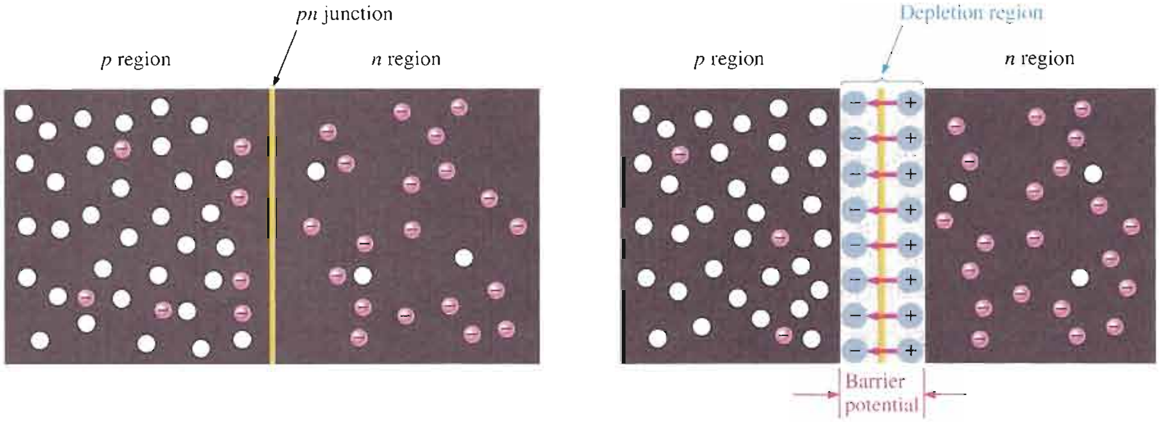
Formation of the Depletion Region

As you have seen, 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 1–18(a).

▶ **FIGURE 1–17**

The basic diode structure at the instant of junction formation showing only the majority and minority carriers.





(a) At the instant of junction formation, 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.

▲ **FIGURE 1–18**

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

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 1–18(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 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 a "field of forces" called an *electric field*, as illustrated in Figure 1–18(b) by the red 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.

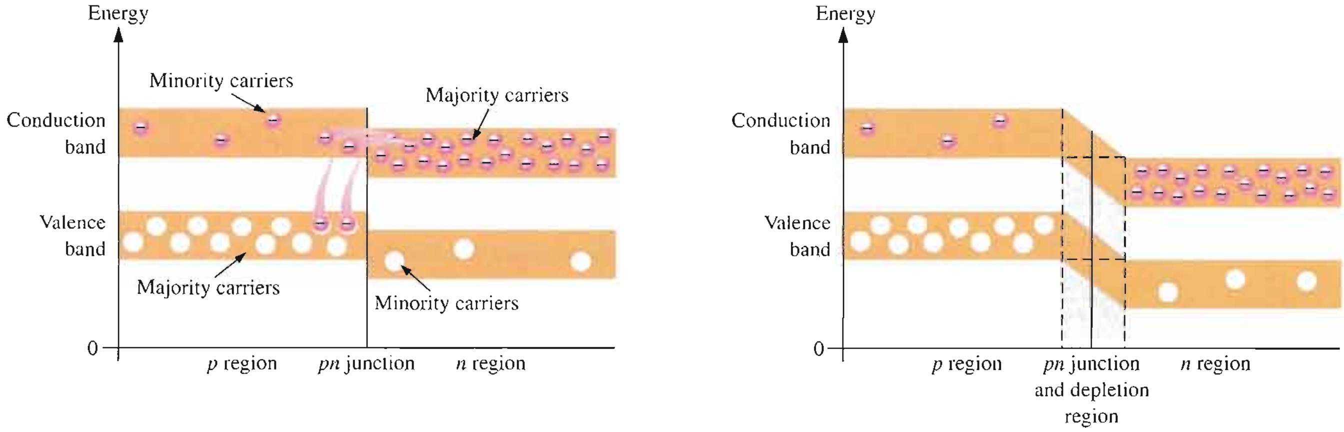
The potential difference of the electric field across the depletion region is the amount of voltage required to move electrons through the electric field. This potential difference is called the **barrier potential** and is expressed in volts. Stated another way, a certain amount of voltage equal to 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 Section 1–7.

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. Throughout the rest of the book, silicon will be used unless otherwise stated.

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. This is due to differences in the atomic characteristics of the pentavalent and the trivalent impurity atoms.

An energy diagram for a *pn* junction at the instant of formation is shown in Figure 1–19(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.



(a) At the instant of junction formation

(b) At equilibrium

▲ **FIGURE 1–19**

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

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 1–19(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 1-19(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.

SECTION 1-6 REVIEW

1. What is a *pn* junction?
2. Explain what diffusion is.
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?

1–7 BIASING A DIODE

As you have learned, no electrons move through the *pn* junction at equilibrium. Generally the term *bias* refers to the use of a dc voltage to establish certain operating conditions for an electronic device. In relation to a diode, there are two bias conditions: forward and reverse. Either of these bias conditions is established by connecting a sufficient dc voltage of the proper polarity across the *pn* junction.

After completing this section, you should be able to

- **Discuss the bias of a diode**
- Define *forward bias* and state the required conditions
- Define *reverse bias* and state the required conditions
- Discuss the effect of barrier potential on forward bias
- Explain how current is produced in forward bias
- Explain reverse current
- Describe reverse breakdown of a diode
- Explain forward bias and reverse bias in terms of energy diagrams

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 1–20 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, R, limits the current to a value that will not damage the diode.

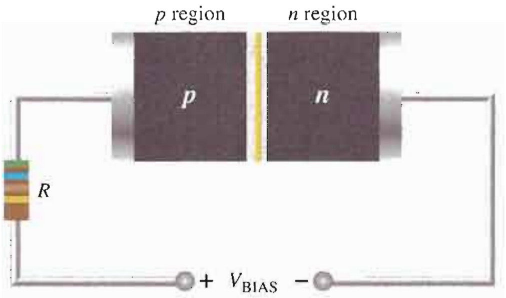


FIGURE 1–20

A diode connected for forward bias.

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.

A fundamental picture of what happens when a diode is forward-biased is shown in Figure 1–21. 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.

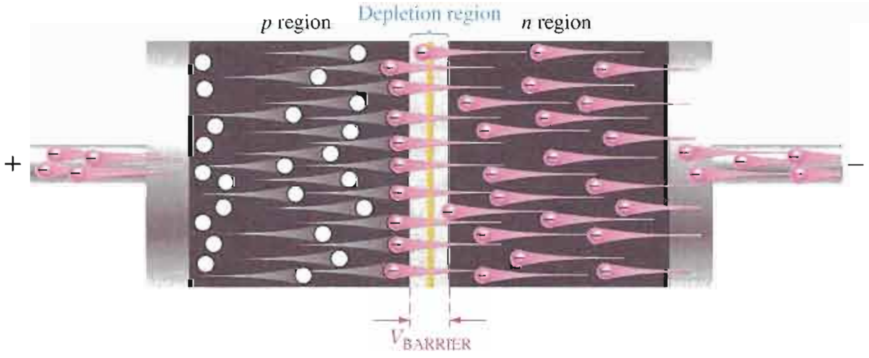


FIGURE 1–21

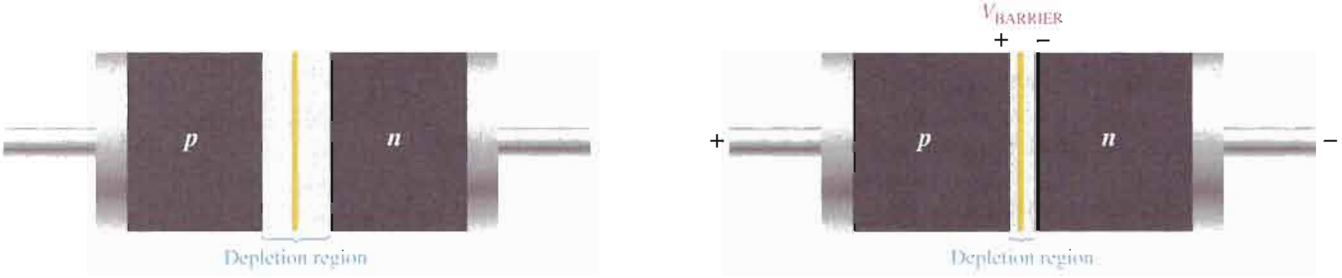
A forward-biased diode showing the flow of majority carriers and the voltage due to the barrier potential across the depletion region.

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.

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 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 1–21. This *effective* flow of holes is called 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. So, 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 1–22.



(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 1–22

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 (see Figure 1–19(b)). 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 1–22(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 1–8.

Reverse Bias

Reverse bias is the condition that essentially prevents current through the diode. Figure 1–23 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.

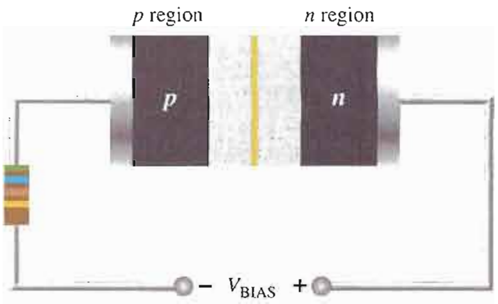


FIGURE 1–23

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 1–24. 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.

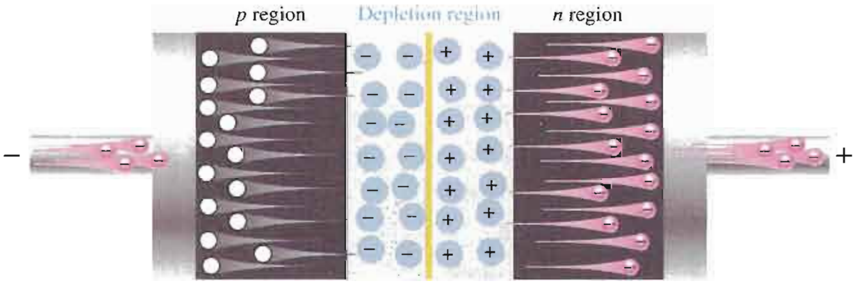


FIGURE 1–24

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.

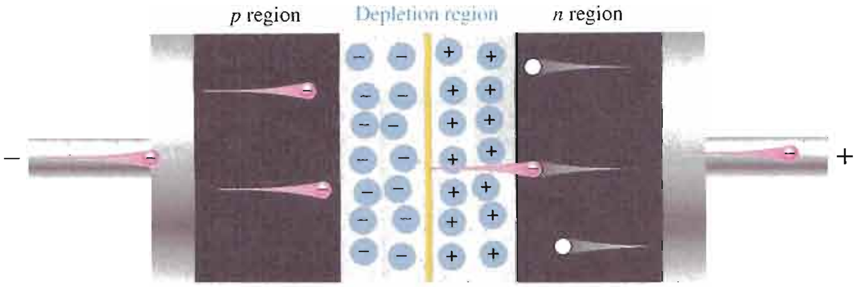
Reverse Current The extremely small current that exists in reverse bias after the transition current dies out is caused by the minority carriers in the *n* and *p* regions that are produced by thermally generated electron-hole pairs. The small number of free minority electrons in the *p* region are "pushed" 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 1–25.

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.

FIGURE 1–25

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



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 **avalanche** and results in a very high reverse current that can damage the diode because of excessive heat dissipation.

SECTION 1–7 REVIEW

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* as applied to diodes.

1–8 VOLTAGE-CURRENT CHARACTERISTIC OF A DIODE

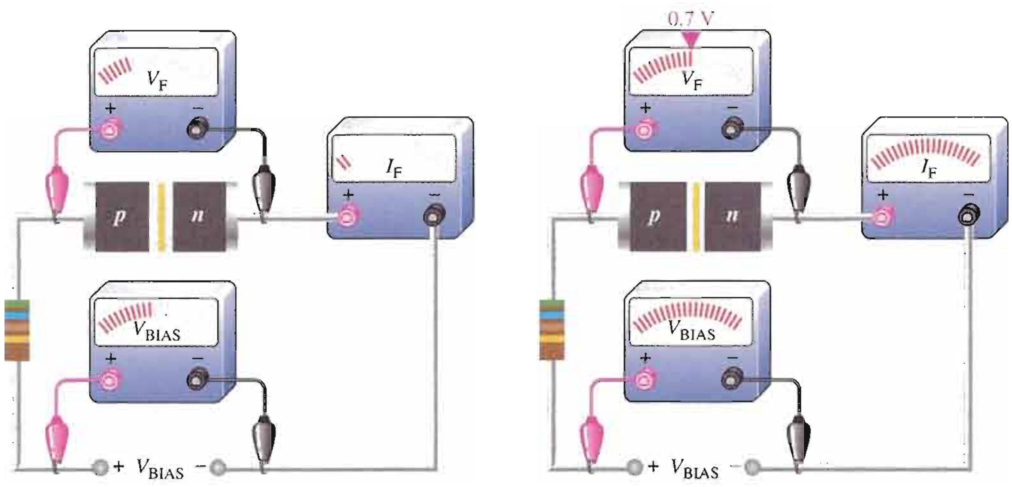
As you have learned, forward bias produces current through a diode and reverse bias essentially prevents current, except for a negligible reverse current. Reverse bias prevents current as long as the reverse-bias voltage does not equal or exceed the breakdown voltage of the junction. In this section, we will examine more closely 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 curve of a diode**
- Explain the forward-bias portion of the *V-I* characteristic curve
- Explain the reverse-bias portion of the *V-I* characteristic curve
- Identify the barrier potential
- Identify the breakdown voltage
- Discuss temperature effects on a diode

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 1–26 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.



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

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

▲ **FIGURE 1–26**

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

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 1–26(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 1–26(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.

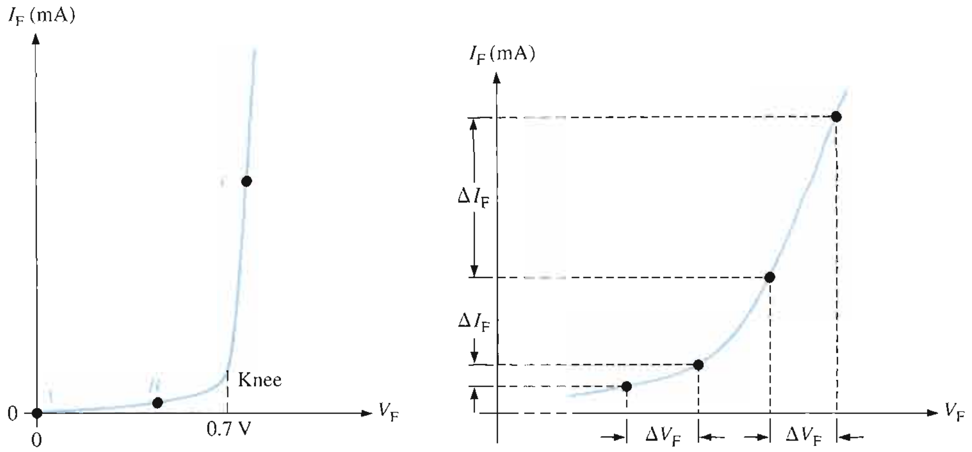
Graphing the V-I Curve If you plot the results of the type of measurements shown in Figure 1–26 on a graph, you get the ***V-I* characteristic** curve for a forward-biased diode, as shown in Figure 1–27(a). The diode forward voltage (V_F) increases to the right along the horizontal axis, and the forward current (I_F) increases upward along the vertical axis.

As you can see in Figure 1–27(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 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. *Normal operation for a forward-biased diode is above the knee of the curve.* The I_F scale is typically in mA, as indicated.

Three points *A*, *B*, and *C* are shown on the curve in Figure 1–27(a). Point *A* corresponds to a zero-bias condition. Point *B* corresponds to Figure 1–26(a) where the forward voltage is less than the barrier potential of 0.7 V. Point *C* corresponds to Figure 1–26(a) where the

FIGURE 1–27

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



(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 $\Delta V_F/\Delta I_F$.

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 0.90 V, depending on the forward current.

Dynamic Resistance Figure 1–27(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.*

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 1–28. 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

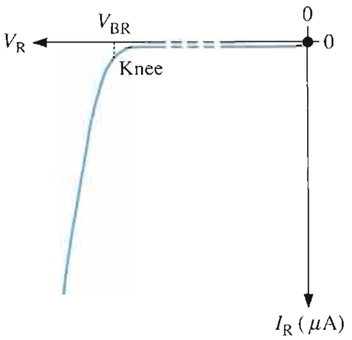


FIGURE 1–28

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

point, the reverse voltage remains at approximately V_{BR}, but I_R increases very rapidly, resulting in overheating and possible damage. The breakdown voltage for a typical silicon diode can vary, but a minimum value of 50 V is not unusual.

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 1–29. Notice that the I_F scale is in mA compared to the I_R scale in μA.

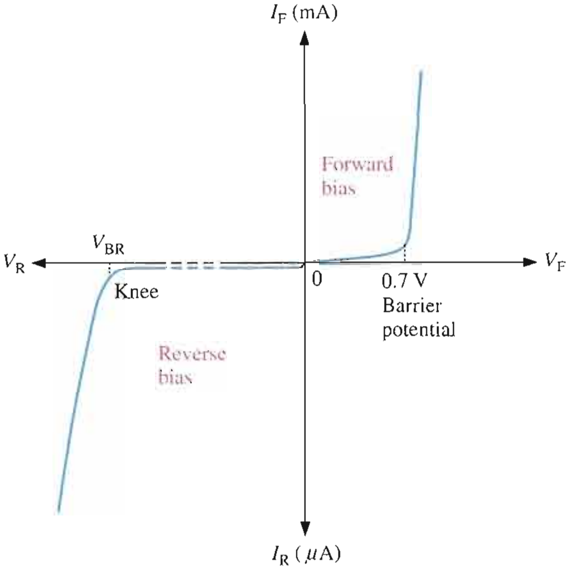
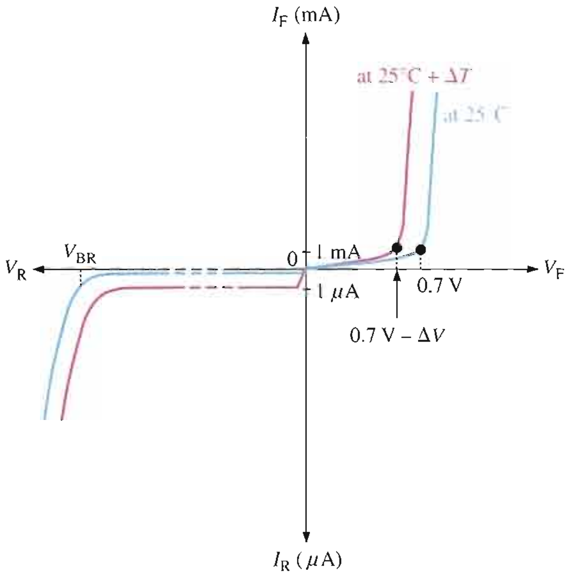


FIGURE 1–29

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 1–30. The blue curve is at room temperature (25°C) and the red curve is at an elevated temperature (25°C + ΔT). Notice that the barrier potential decreases as temperature increases.

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 1–30 for illustration. Keep in mind that the reverse current below breakdown remains extremely small and can usually be neglected.



▶ **FIGURE 1–30**

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.

SECTION 1–8 REVIEW

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?

1–9 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 the diode can be modeled for circuit analysis using three levels of complexity. Also, diode packaging and terminal identification are introduced.

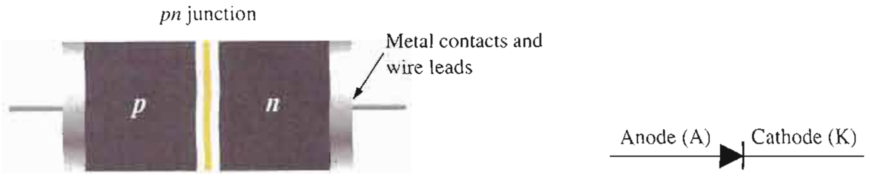
After completing this section, you should be able to

- **Discuss the operation of diodes and explain the three diode models**
- Recognize a diode symbol and indentify the diode terminals
- Recognize diodes in various physical configurations
- Explain the ideal, the practical, and the complete diode models

Diode Structure and Symbol

A diode is a single *pn* junction device with conductive contacts and wire leads connected to each region, as shown in Figure 1–31(a). Part of the diode is an *n*-type semiconductor and the other part is a *p*-type semiconductor.

There are several types of diodes, but the schematic symbol for a general-purpose or rectifier diode, such as introduced in this chapter, is shown in Figure 1–31(b). The *n* region is called the **cathode** and the *p* region is called the **anode**. The "arrow" in the symbol points in the direction of conventional current (opposite to electron flow).



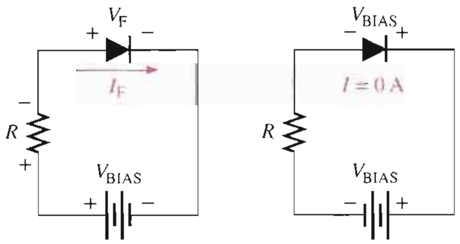
(a) Basic diode structure

(b) Schematic symbol

FIGURE 1–31

Diode structure and schematic symbol.

Forward-Bias Connection A diode is forward-biased when a voltage source is connected as shown in Figure 1–32(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 anode to cathode as indicated. The forward voltage drop (V_F) due to the barrier potential is from positive at the anode to negative at the cathode.



(a) Forward bias

(b) Reverse bias

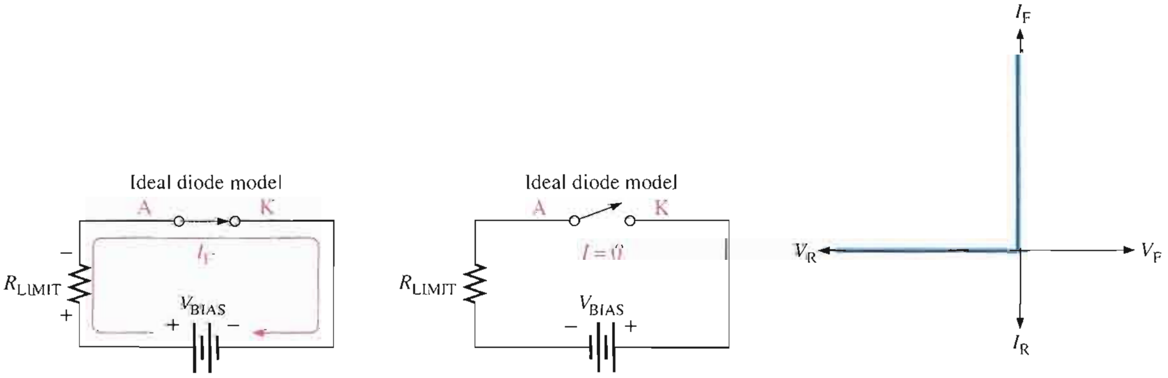
FIGURE 1–32

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 1–32(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.

The Ideal Diode Model

The ideal model of a diode is a simple switch. When the diode is forward-biased, it acts like a closed (on) switch, as shown in Figure 1–33(a). When the diode is reverse-biased, it acts like an open (off) switch, as shown in part (b). The barrier potential, the forward dynamic resistance, and the reverse current are all neglected.



(a) Forward bias

(b) Reverse bias

(c) Ideal characteristic curve (blue)

FIGURE 1–33

The ideal model of a diode.

In Figure 1–33(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.

Equation 1–2

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

Since the reverse current is neglected, its value is assumed to be zero, as indicated in Figure 1–33(c) by the portion of the curve on the negative horizontal axis.

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

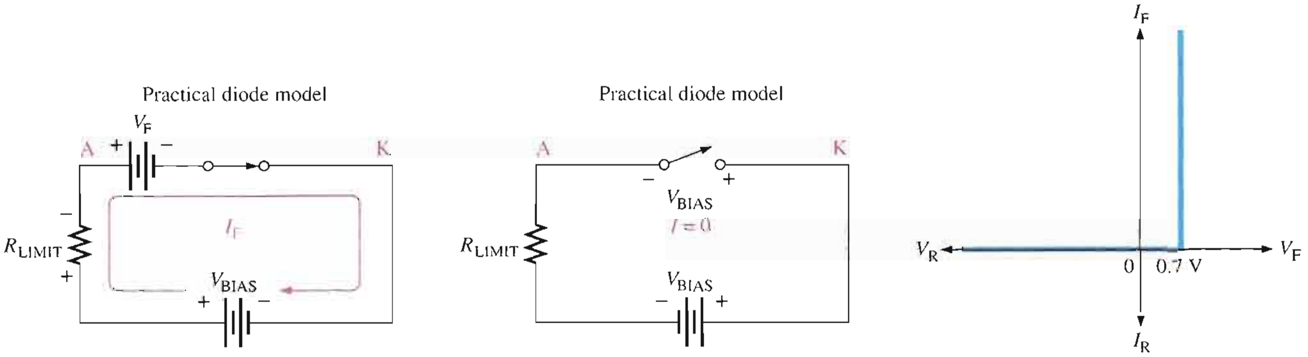
The reverse voltage equals the bias voltage.

$$V_R = V_{BIAS}$$

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 adds the barrier potential to the ideal switch model. When the diode is forward-biased, it is equivalent to a closed switch in series with a small equivalent voltage source equal to the barrier potential (0.7 V) with the positive side toward the anode, as indicated in Figure 1–34(a). This equivalent voltage source represents the fixed voltage drop (V_F) produced across the forward-biased *pn* junction of the diode and is not an active source of voltage.



(a) Forward bias

(b) Reverse bias

(c) Characteristic curve (silicon)

▲ **FIGURE 1–34**

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 1–34(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 1–34(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 1–34(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},

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

Equation 1–3

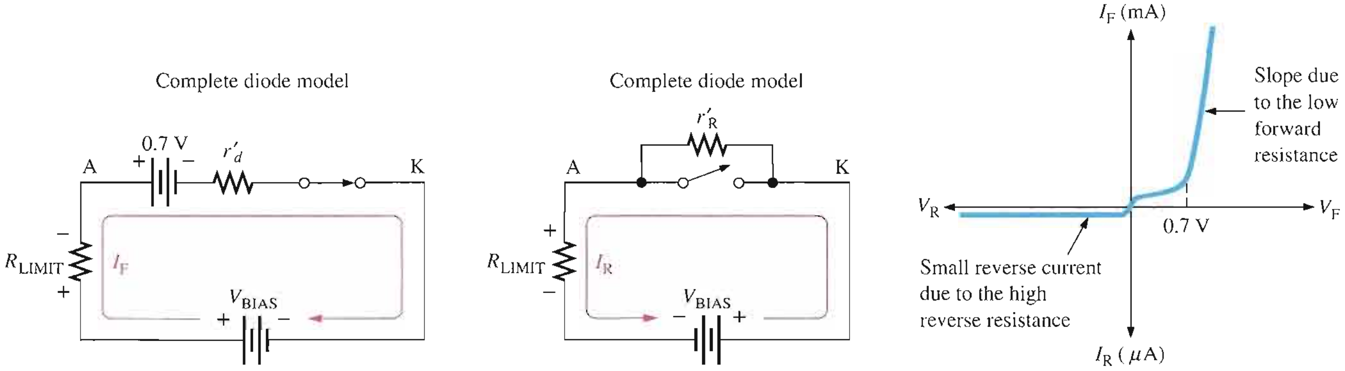
The diode is assumed to have zero reverse current, as indicated by the portion of the curve on the negative horizontal axis.

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

The Complete Diode Model

The complete model of a diode consists of 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 barrier potential voltage and the small forward dynamic resistance (r'_d), as indicated in Figure 1–35(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 1–35(b). The barrier potential does not affect reverse bias, so it is not a factor.



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

▲ **FIGURE 1–35**

The complete model of a diode.

The characteristic curve for the complete diode model is shown in Figure 1–35(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:

$$V_{\text{F}} = 0.7\text{ V} + I_{\text{F}} r'_d$$

Equation 1–4

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

Equation 1–5

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.

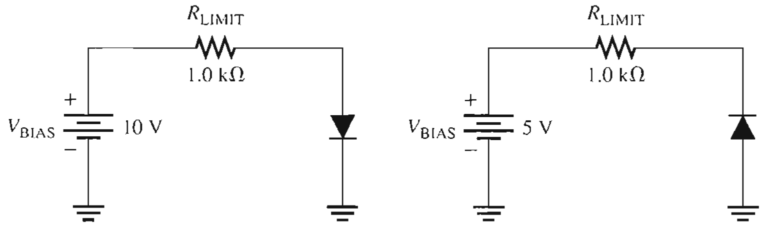
Although the ideal and practical models are predominately used in this textbook, the following example illustrates the differences in all three diode models in the analysis of a simple circuit.

EXAMPLE 1–1

(a) Determine the forward voltage and forward current for the diode in Figure 1–36(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 1-36(b) for each of the diode models. Also find the voltage across the limiting resistor in each case. Assume $I_R = 1\ \mu A$.

FIGURE 1–36



(a) (b)

Solution **(a)** Ideal model:

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

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

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

Practical model:

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

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

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

Complete model:

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

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

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

$$I_R = \mathbf{0\ A}$$
$$V_R = V_{BIAS} = \mathbf{5\ V}$$
$$V_{R_{LIMIT}} = \mathbf{0\ V}$$

Practical model:

$$I_R = \mathbf{0\ A}$$
$$V_R = V_{BIAS} = \mathbf{5\ V}$$
$$V_{R_{LIMIT}} = \mathbf{0\ V}$$

Complete model:

$$I_R = \mathbf{1\ \mu A}$$
$$V_{R_{LIMIT}} = I_R R_{LIMIT} = (1\ \mu\text{A})(1.0\ \text{k}\Omega) = \mathbf{1\ mV}$$
$$V_R = V_{BIAS} - V_{R_{LIMIT}} = 5\ \text{V} - 1\ \text{mV} = \mathbf{4.999\ V}$$

Related Problem* Assume that the diode in Figure 1–36(a) fails open. What is the voltage across the diode and the voltage across the limiting resistor?

---

*Answers are at the end of the chapter.

Open the Multisim file E01-01 in the Examples folder on your CD-ROM. Measure the voltages across the diode and the resistor in both circuits and compare with the calculated results in this example.

Typical Diodes

Several common physical configurations of diodes are illustrated in Figure 1–37. The anode and cathode 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. Always check the data sheet, which will be introduced in Chapter 2, for the pin configuration if there is uncertainty.

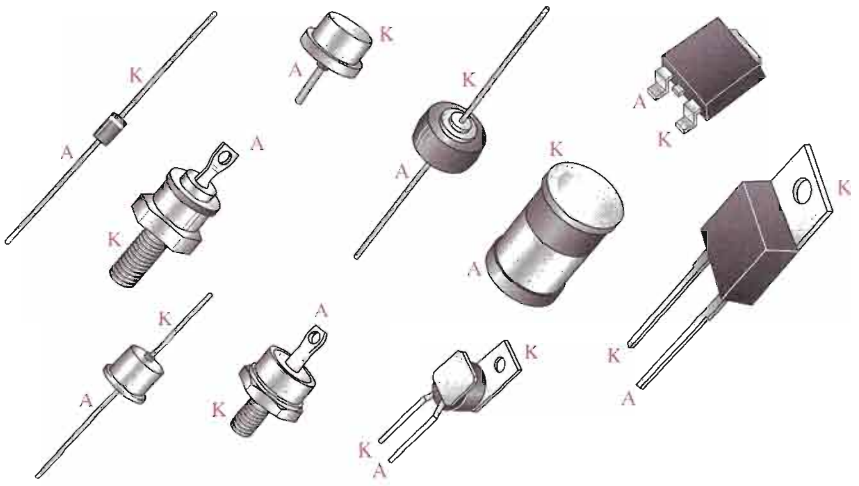


FIGURE 1–37

Typical diode packages with terminal identification.

SECTION 1–9 REVIEW

1. What are the two conditions under which the diode is operated?
2. Under what condition is the 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 models will be used in this book?

1–10 TESTING A DIODE

A multimeter can be used as a fast and simple way to check a diode. 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.

After completing this section, you should be able to

- **Test a diode using a digital multimeter**
- Identify a properly functioning diode
- Identify a faulty diode

The DMM Diode Test Position Many digital multimeters (DMMs) have a diode test position that provides a convenient way to test a diode. A typical DMM, as shown in Figure 1–38, 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 1–38(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 1–38(b), the diode is turned around to reverse-bias the diode as shown. If the diode is working properly, you will get a voltage reading based on the meter's internal voltage source. The 2.6 V shown in the figure represents a typical value and indicates that the diode has an extremely high reverse resistance with essentially all of the internal voltage appearing across it.

When the Diode Is Defective When a diode has failed open, you get an open circuit voltage reading (2.6 V is typical) or "OL" indication for both the forward-bias and the reverse-bias condition, as illustrated in Figure 1–39(a). If a diode is shorted, the meter reads 0 V in both forward- and reverse-bias tests, as indicated in part (b). Sometimes, a failed diode may exhibit a small resistance for both bias conditions rather than a pure short. In this case, the meter will show a small voltage much less than the correct open voltage. For example, a resistive diode may result in a reading of 1.1 V in both directions rather than the correct readings of 0.7 V for forward bias and 2.6 V for reverse bias.

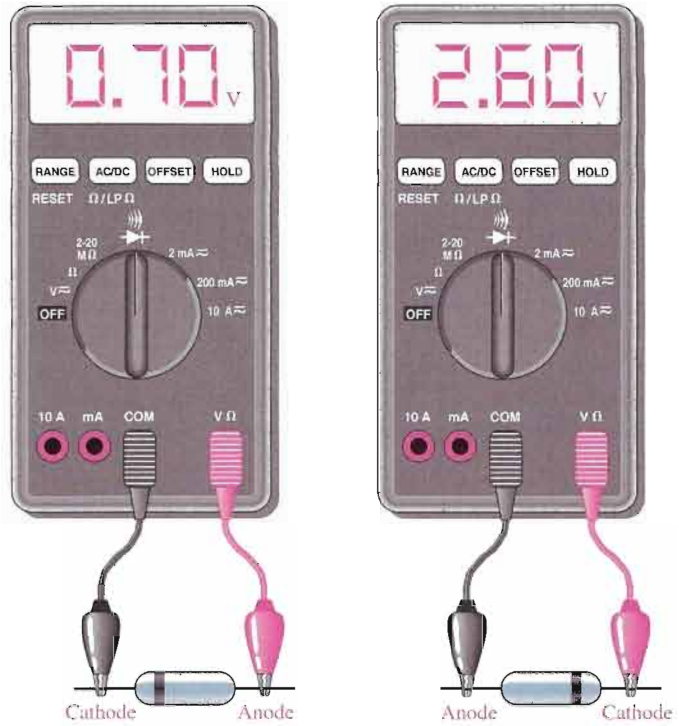


FIGURE 1–38

DMM diode test on a properly functioning diode.

(a) Forward-bias test

(b) Reverse-bias test

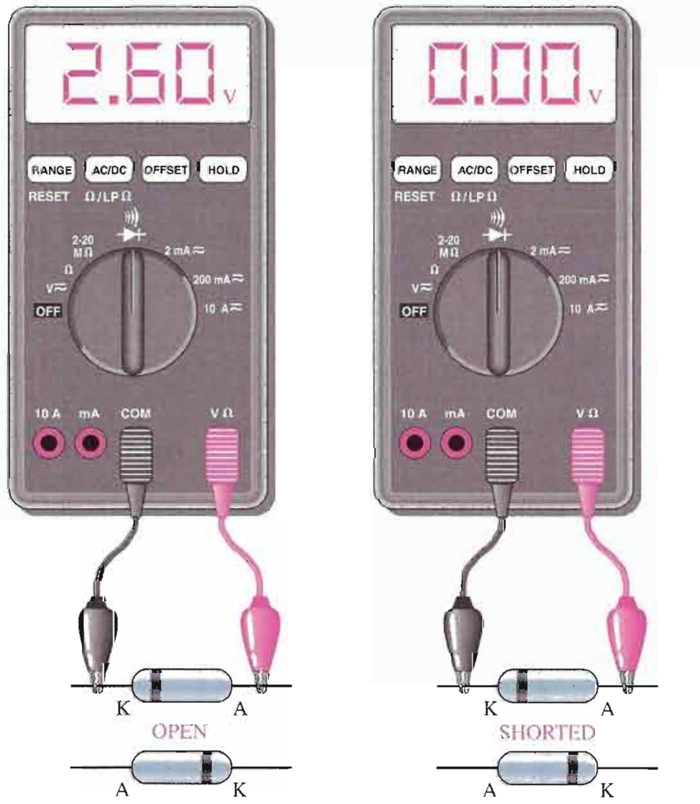


FIGURE 1–39

Testing a defective diode.

(a) Forward- and reverse-bias tests for an open diode give the same indication. Some meters will display “OL.”

(b) Forward- and reverse-bias tests for a shorted diode give the same 0 V reading. If the diode is resistive, the reading is less than 2.6 V.

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

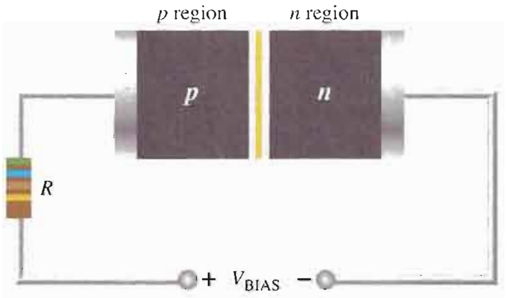
Even though you may not get accurate forward- and reverse-resistance readings on a DMM, the relative readings indicate that a diode is functioning properly, and that is usually all you need to know. The out-of-range indication shows that the reverse resistance is extremely high, as you expect. The reading 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.

SECTION 1–10 REVIEW

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?

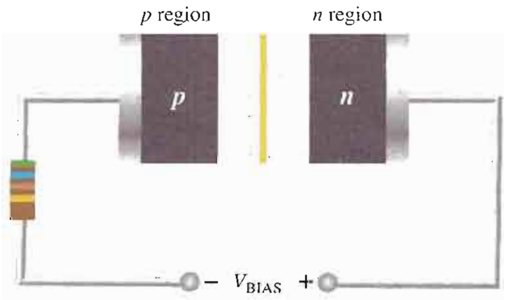
SUMMARY OF DIODE BIAS

FORWARD BIAS: PERMITS MAJORITY-CARRIER CURRENT



- Bias voltage connections: positive to *p* region; negative to *n* region.
- The bias voltage must be greater than the barrier potential.
- Barrier potential: 0.7 V for silicon.
- Majority carriers flow toward the *pn* junction.
- Majority carriers provide the forward current.
- The depletion region narrows.

REVERSE BIAS: PREVENTS MAJORITY-CARRIER CURRENT



- Bias voltage connections: positive to *n* region; negative to *p* region.
- The bias voltage must be less than the breakdown voltage.
- Majority carriers flow away from the *pn* junction during short transition time.
- Minority carriers provide the extremely small reverse current.
- There is no majority carrier current after transition time.
- The depletion region widens.

CHAPTER SUMMARY

- 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.
- 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.
- Semiconductor atoms have four valence electrons. Silicon is the most widely used semiconductive material.
- Materials that are conductors have a large number of free electrons and conduct current very well. Insulating materials have very few free electrons and do not conduct current at all under normal circumstances. Semiconductive materials fall in between conductors and insulators in their ability to conduct current.
- 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*. Within the crystal structure, 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.
- 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.
- 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.
- 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.
- The forward-biased barrier potential is typically 0.7 V for a silicon diode. These values increase slightly with forward current.
- Reverse breakdown voltage for a diode is typically greater than 50 V.
- An ideal diode presents an open when reversed-biased and a short when forward-biased.

KEY TERMS

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

Anode The *p* region of a diode.

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.

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

Cathode The *n* region of a diode.

Conductor A material that easily conducts electrical current.

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

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

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.

Forward bias The condition in which a diode conducts current.

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.

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

Proton The basic particle of positive charge.

Reverse bias The condition in which a diode prevents current.

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.

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

KEY FORMULAS

1–1	$N_e = 2n^2$	Maximum number of electrons in any shell
1–2	$I_F = \dfrac{V_{BIAS}}{R_{LIMIT}}$	Forward current, ideal diode model
1–3	$I_F = \dfrac{V_{BIAS} - V_F}{R_{LIMIT}}$	Forward current, practical diode model
1–4	$V_F = 0.7\text{ V} + I_F r'_d$	Forward voltage, complete diode model
1–5	$I_F = \dfrac{V_{BIAS} - 0.7\ V}{R_{LIMIT} + r'_d}$	Forward current, complete diode model

CIRCUIT-ACTION QUIZ

Answers are at the end of the chapter.

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

SELF-TEST

Answers are at the end of the chapter.

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. The atomic number of silicon is
   (a) 8 (b) 2 (c) 4 (d) 14
5. The atomic number of germanium is
   (a) 8 (b) 2 (c) 4 (d) 32
6. The valence shell in a silicon atom has the number designation of
   (a) 0 (b) 1 (c) 2 (d) 3
7. 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
8. 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
9. The most widely used semiconductive material in electronic devices is
   (a) germanium (b) carbon (c) copper (d) silicon
10. The energy band in which free electrons exist is the
    (a) first band (b) second band (c) conduction band (d) valence band
11. Electron-hole pairs are produced by
    (a) recombination (b) thermal energy (c) ionization (d) doping

12. 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

13. 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)

14. 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

15. The current in a semiconductor is produced by
(**a**) electrons only (**b**) holes only (**c**) negative ions (**d**) both electrons and holes

16. 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)

17. 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)

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

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)

26. 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)

27. 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)

28. 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

29. 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

30. 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

31. When forward-biased, a diode

(a) blocks current **(b)** conducts current

(c) has a high resistance **(d)** drops a large voltage

32. When a voltmeter is placed across a forward-biased diode, it will read a voltage approximately equal to

(a) the bias battery voltage **(b)** 0 V

(c) the diode barrier potential **(d)** the total circuit voltage

33. A silicon diode is in series with a 1.0 kΩ resistor and a 5 V battery. If the anode is connected to the positive battery terminal, the cathode voltage with respect to the negative battery terminal is

(a) 0.7 V **(b)** 0.3 V **(c)** 5.7 V **(d)** 4.3 V

34. The positive lead of an ohmmeter is connected to the anode of a diode and the negative lead is connected to the cathode. The diode is

(a) reversed-biased **(b)** open **(c)** forward-biased

(d) faulty **(e)** answers (b) and (d)

PROBLEMS

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

BASIC PROBLEMS

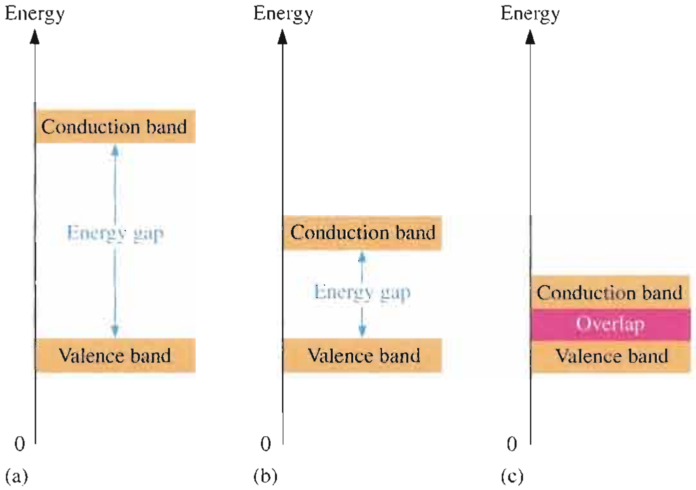
SECTION 1–1 Atomic Structure

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 Semiconductors, Conductors, and Insulators

3. For each of the energy diagrams in Figure 1–40, determine the class of material based on relative comparisons.
4. A certain atom has four valence electrons. What type of atom is it?

▶ FIGURE 1–40



SECTION 1–3 Covalent Bonds

5. In a silicon crystal, how many covalent bonds does a single atom form?

SECTION 1–4 Conduction 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 1–5 *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 1–6 The Diode

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.

SECTION 1–7 Biasing a Diode

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

SECTION 1–8 Voltage-Current Characteristic of a Diode

14. Explain how to generate the forward-bias portion of the characteristic curve.
15. What would cause the barrier potential to decrease from 0.7 V to 0.6 V?

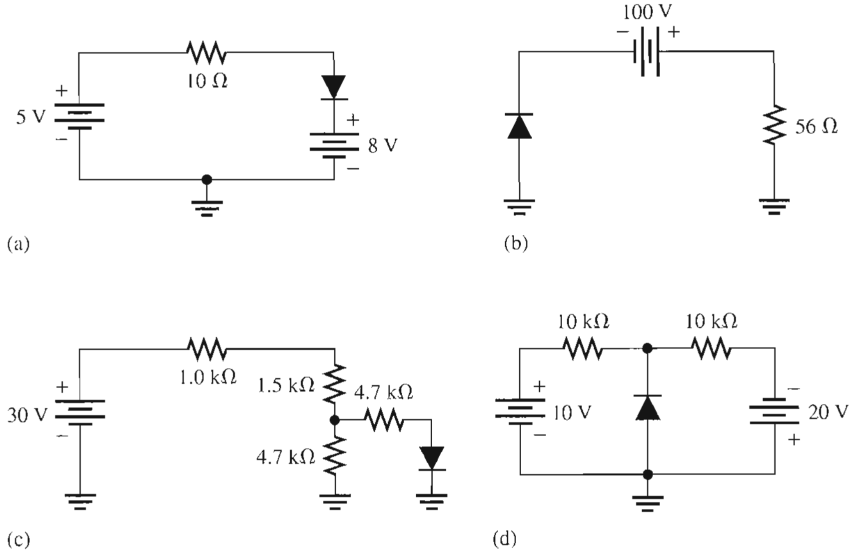
SECTION 1–9 Diode Models

16. Determine whether each diode in Figure 1–41 is forward-biased or reverse-biased.

17. Determine the voltage across each diode in Figure 1–41, assuming the practical model.

FIGURE 1–41

Multisim file circuits are identified with a CD logo and are in the Problems folder on your CD-ROM. Filenames correspond to figure numbers (e.g., F01-41).



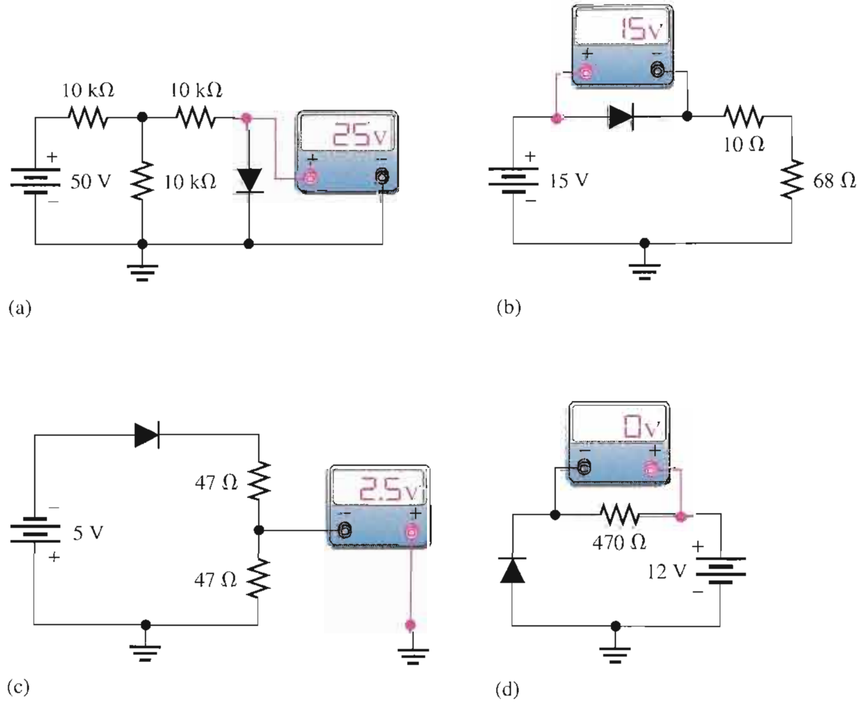
(a) (b) (c) (d)

TROUBLESHOOTING PROBLEMS

SECTION 1–10 Testing a Diode

18. Consider the meter indications in each circuit of Figure 1–42, and determine whether the diode is functioning properly, or whether it is open or shorted. Assume the ideal model.

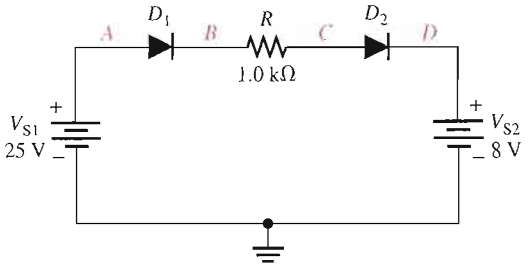
FIGURE 1–42



(a) (b) (c) (d)

19. Determine the voltage with respect to ground at each point in Figure 1–43. Assume the practical model.

FIGURE 1–43



MULTISIM TROUBLESHOOTING PROBLEMS

These file circuits are in the Troubleshooting Problems folder on your CD-ROM.

20. Open file TSP01-20 and determine the fault.
21. Open file TSP01-21 and determine the fault.
22. Open file TSP01-22 and determine the fault.
23. Open file TSP01-23 and determine the fault.
24. Open file TSP01-24 and determine the fault.
25. Open file TSP01-25 and determine the fault.
26. Open file TSP01-26 and determine the fault.
27. Open file TSP01-27 and determine the fault.
28. Open file TSP01-28 and determine the fault.

ANSWERS

SECTION REVIEWS

SECTION 1–1 Atomic Structure

1. An atom is the smallest particle of an element that retains the characteristics of that element.
2. An electron is the basic particle of negative electrical charge.
3. A valence electron is an electron in the outermost shell of an atom.
4. A free electron is one that has acquired enough energy to break away from the valence band of the parent atom.
5. When a neutral atom loses an electron, the atom becomes a positive ion. When a neutral atom gains an electron, the atom becomes a negative ion.

SECTION 1–2 Semiconductors, Conductors, and Insulators

1. Conductors have many free electrons and easily conduct current. Insulators have essentially no free electrons and do not conduct current.
2. Semiconductors do not conduct current as well as conductors do. In terms of conductivity, they are between conductors and insulators.
3. Conductors such as copper have one valence electron.
4. Semiconductors have four valence electrons.
5. Gold, silver, and copper are the best conductors.
6. Silicon is the most widely used semiconductor.
7. The valence electrons of a semiconductor are more tightly bound to the atom than those of conductors.

SECTION 1–3 Covalent Bonds

1. Covalent bonds are formed by the sharing of valence electrons with neighboring atoms.
2. An intrinsic material is one that is in a pure state.
3. A crystal is a solid material formed by atoms bonding together in a fixed pattern.
4. There are eight shared valence electrons in each atom of a silicon crystal.

SECTION 1–4 Conduction in Semiconductors

1. Free electrons are in the conduction band.
2. Free (conduction) electrons are responsible for current in a material.
3. A hole is the absence of an electron in the valence band.
4. Hole current occurs at the valence level.

SECTION 1–5 *N*-Type and *P*-Type Semiconductors

1. Doping is the process of adding impurity atoms to a semiconductor in order to modify its conductive properties.
2. A pentavalent atom (donor) has five valence electrons and a trivalent atom (acceptor) has three valence electrons.
3. An *n*-type material is formed by the addition of pentavalent impurity atoms to the intrinsic semiconductive material.
4. A *p*-type material is formed by the addition of trivalent impurity atoms to the intrinsic semiconductive material.
5. The majority carrier in an *n*-type semiconductor is the free electron.
6. The majority carrier in a *p*-type semiconductor is the hole.
7. Majority carriers are produced by doping.
8. Minority carriers are thermally produced when electron-hole pairs are generated.
9. A pure semiconductor is intrinsic. A doped (impure) semiconductor is extrinsic.

SECTION 1–6 The Diode

1. A *pn* junction is the boundary between *p*-type and *n*-type semiconductors in a diode.
2. Diffusion is the movement of the free electrons (majority carriers) in the *n*-region across the *pn* junction and into the *p* region.
3. The depletion region is the thin layers of positive and negative ions that exist on both sides of the *pn* junction.
4. The barrier potential is the potential difference of the electric field in the depletion region and is the amount of energy required to move electrons through the depletion region.
5. The barrier potential for a silicon diode is approximately 0.7 V.
6. The barrier potential for a germanium diode is approximately 0.3 V.

SECTION 1–7 Biasing a Diode

1. When forward-biased, a diode conducts current. The free electrons in the *n* region move across the *pn* junction and combine with the holes in the *p* region.
2. To forward-bias a diode, the positive side of an external bias voltage is applied to the *p* region and the negative side to the *n* region.
3. When reverse-biased, a diode does not conduct current except for an extremely small reverse current.
4. To reverse-bias a diode, the positive side of an external bias voltage is applied to the *n* region and the negative side to the *p* region.
5. The depletion region for forward bias is much narrower than for reverse bias.
6. Majority carrier current is produced by forward bias.
7. Reverse current is produced by the minority carriers.

8. Reverse breakdown occurs when the reverse-bias voltage equals or exceeds the breakdown voltage of the *pn* junction of a diode.
9. Avalanche is the rapid multiplication of current carriers in reverse breakdown.

SECTION 1–8 Voltage-Current Characteristic of a Diode

1. The knee of the characteristic curve in forward bias is the point at which the barrier potential is overcome and the current increases drastically.
2. A forward-biased diode is normally operated above the knee of the curve.
3. Breakdown voltage is always much greater than the barrier potential.
4. A reverse-biased diode is operated below the breakdown point on the knee of the curve.
5. Barrier potential decreases as temperature increases.

SECTION 1–9 Diode Models

1. The diode is operated in forward bias and reverse bias.
2. The diode should never be operated in reverse breakdown.
3. The diode can be ideally viewed as a switch.
4. A diode includes barrier potential, dynamic resistance, and reverse resistance in the complete model.
5. The ideal and practical diode models (barrier potential) are used.

SECTION 1–10 Testing a Diode

1. 0.5 V to 0.9 V
2. 2.60 V

RELATED PROBLEM FOR EXAMPLE

1–1 $V_D = 5\text{ V}$; $V_{\text{LIMIT}} = 0\text{ V}$

CIRCUIT-ACTION QUIZ

1. (a) **2.** (c) **3.** (c) **4.** (a)
5. (a) **6.** (c) **7.** (b) **8.** (a)

SELF-TEST

1. (c) **2.** (d) **3.** (a) **4.** (d) **5.** (d) **6.** (d) **7.** (b) **8.** (a) **9.** (d)
10. (c) **11.** (b) **12.** (a) **13.** (d) **14.** (c) **15.** (d) **16.** (e) **17.** (d) **18.** (a)
19. (b) **20.** (c) **21.** (c) **22.** (a) **23.** (c) **24.** (d) **25.** (d) **26.** (c) **27.** (d)
28. (d) **29.** (b) **30.** (b) **31.** (b) **32.** (c) **33.** (d) **34.** (c)