INTRODUCTION TO ELECTRONICS

1

CHAPTER OUTLINE

CHAPTER OBJECTIVES

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

KEY TERMS

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

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INTRODUCTION

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

1–1 THE ATOM

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

After completing this section, you should be able to

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

The Bohr Model

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

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

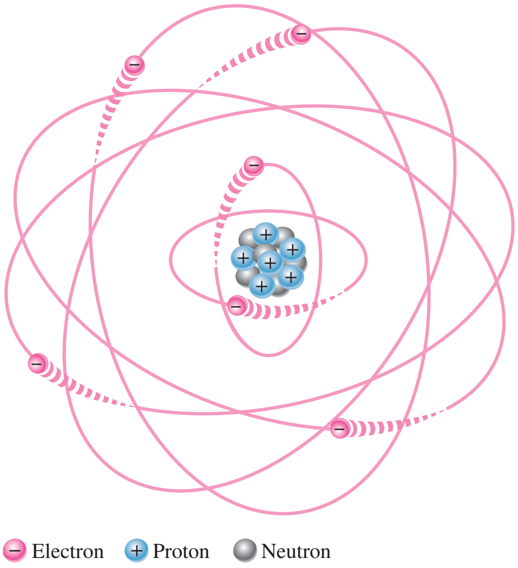
HISTORY NOTE

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

Atomic Number

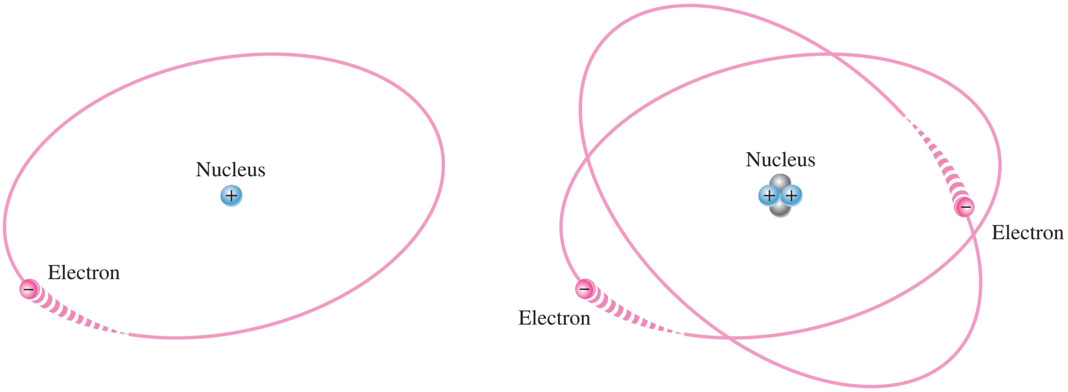
All elements are arranged in the periodic table of the elements in order according to their atomic number. The **atomic number** equals the number of protons in the nucleus, which is the same as the number of electrons in an electrically balanced (neutral) atom. For example, hydrogen has an atomic number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

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



▲ FIGURE 1–1

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



(a) Hydrogen atom

(b) Helium atom

▲ FIGURE 1–2

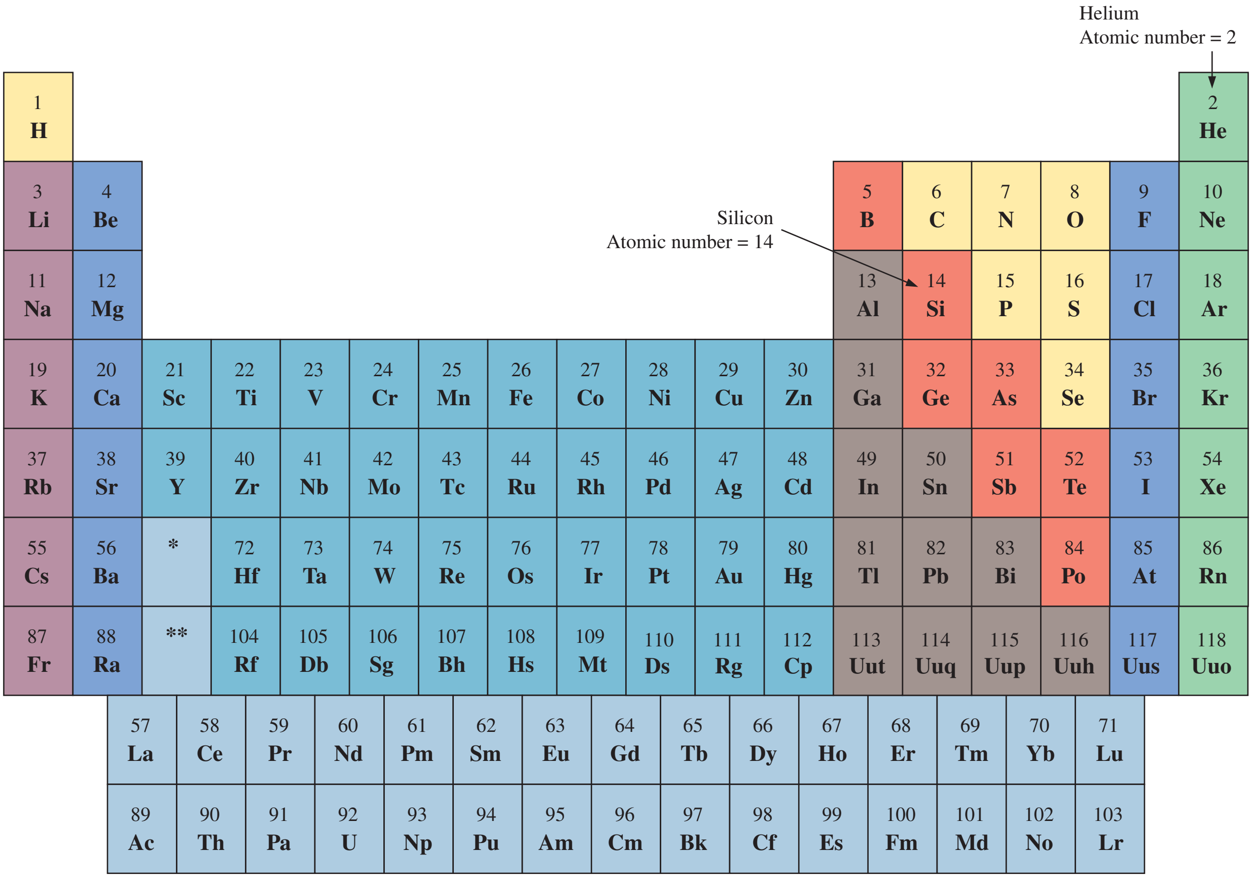
Two simple atoms, hydrogen and helium.

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

Electrons and Shells

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

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



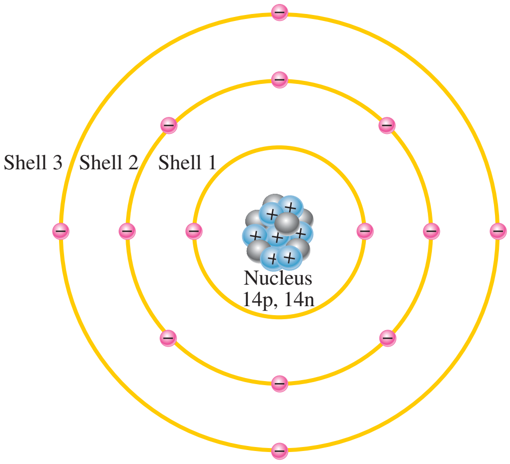
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cp	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

▲ **FIGURE 1–3**

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

▶ **FIGURE 1–4**

Illustration of the Bohr model of the silicon atom.



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

Equation 1–1

$$N_e = 2n^2$$

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

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

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

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

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

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

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

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

Valence Electrons

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

Ionization

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

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

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

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

The Quantum Model

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

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

FYI

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

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

FYI

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

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

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

TABLE 1–1

Electron configuration table for nitrogen.

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

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

EXAMPLE 1–1

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

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

TABLE 1–2

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

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

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

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

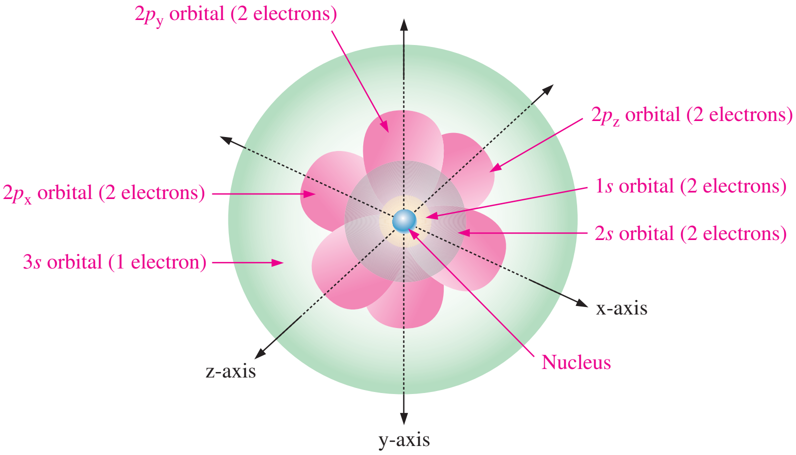


FIGURE 1–5

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

SECTION 1–1 CHECKUP

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

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

1–2 MATERIALS USED IN ELECTRONICS

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

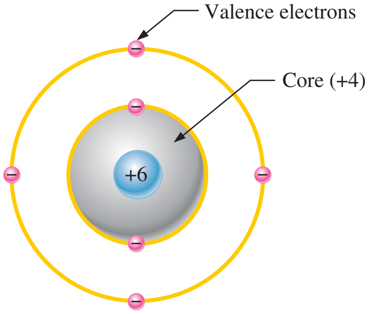
After completing this section, you should be able to

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

Insulators, Conductors, and Semiconductors

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

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



▲ FIGURE 1–6

Diagram of a carbon atom.

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

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

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

Band Gap

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

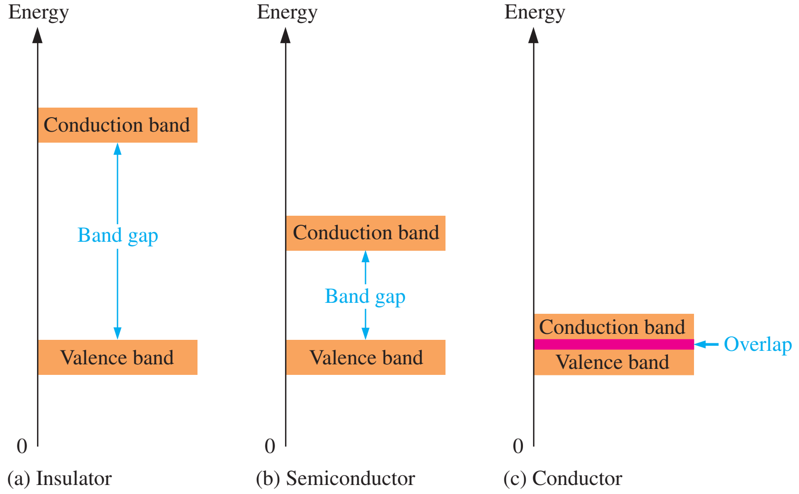
The difference in energy between the valence band and the conduction band is called an *energy gap* or **band gap**. This is the amount of energy that a valence electron must have in order to jump from the valence band to the conduction band. Once in the conduction band, the electron is free to move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

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

FYI

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

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



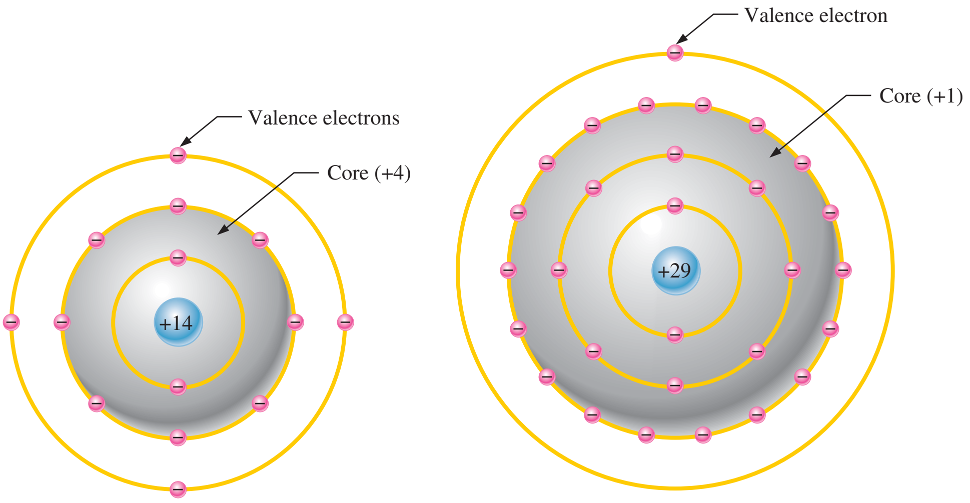
(a) Insulator (b) Semiconductor (c) Conductor

FIGURE 1–7

Energy diagrams for the three types of materials.

Comparison of a Semiconductor Atom to a Conductor Atom

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



(a) Silicon atom (b) Copper atom

FIGURE 1–8

Bohr diagrams of the silicon and copper atoms.

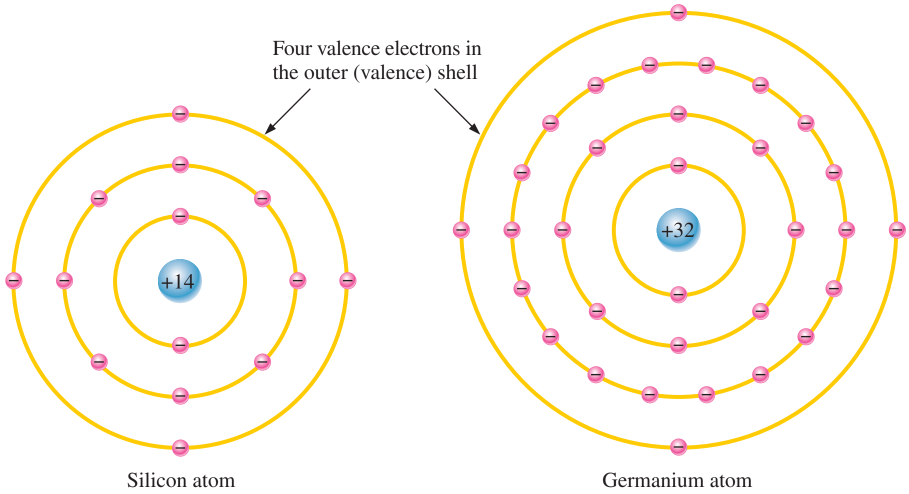
The valence electron in the copper atom “feels” an attractive force of +1 compared to a valence electron in the silicon atom which “feels” an attractive force of +4. Therefore, there is more force trying to hold a valence electron to the atom in silicon than in copper. The copper’s valence electron is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

Silicon and Germanium

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

FIGURE 1–9

Diagrams of the silicon and germanium atoms.

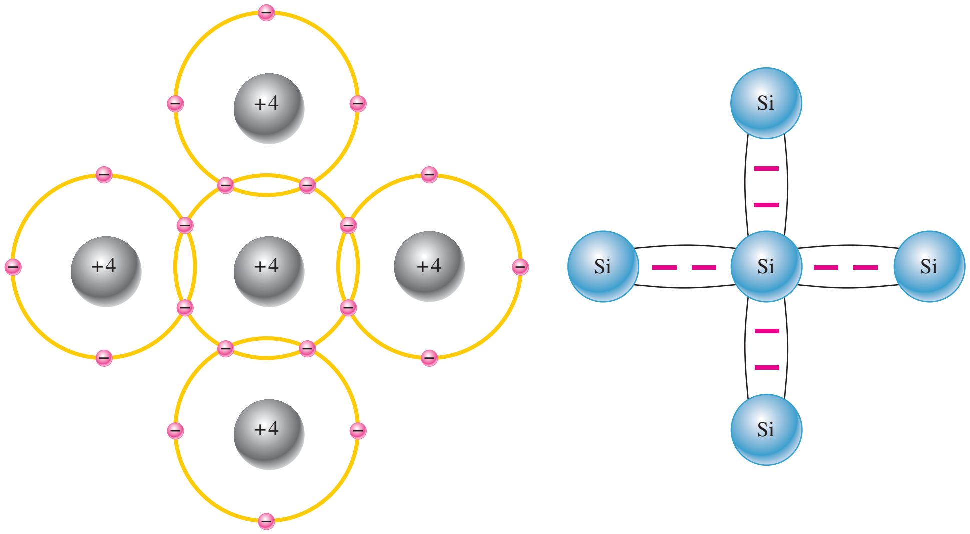


The valence electrons in germanium are in the fourth shell while those in silicon are in the third shell, closer to the nucleus. This means that the germanium valence electrons are at higher energy levels than those in silicon and, therefore, require a smaller amount of additional energy to escape from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

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

FIGURE 1–10

Illustration of covalent bonds in silicon.



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

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

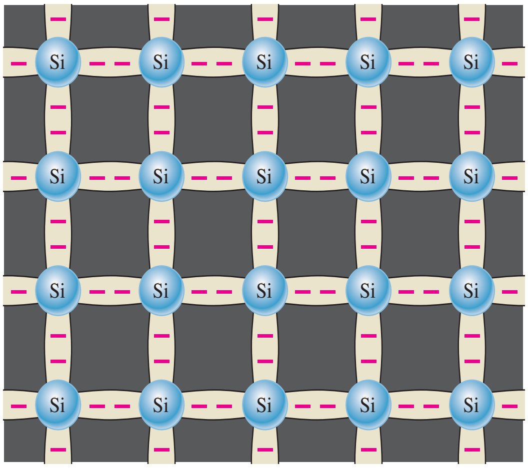


FIGURE 1–11

Covalent bonds in a silicon crystal.

SECTION 1–2 CHECKUP

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

1–3 CURRENT IN SEMICONDUCTORS

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

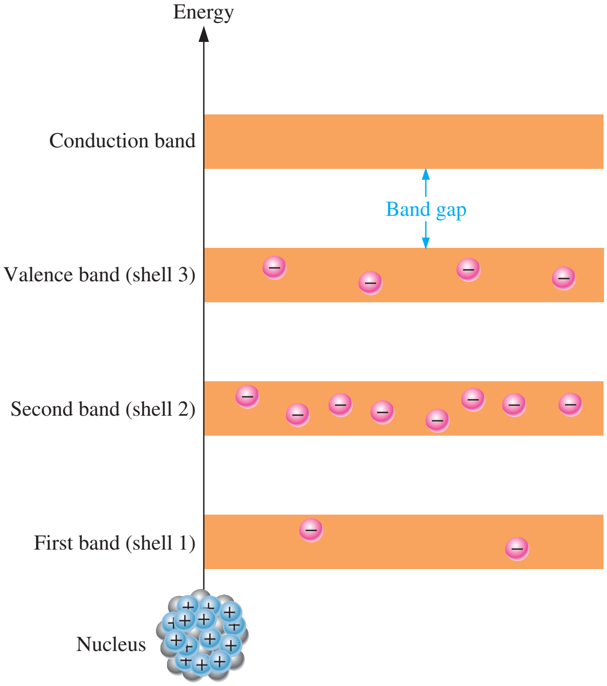
After completing this section, you should be able to

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

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

FIGURE 1–12

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

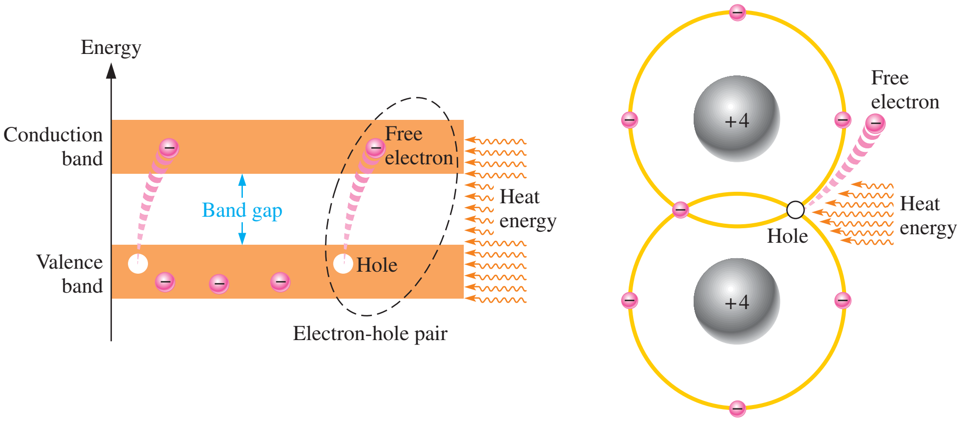


Conduction Electrons and Holes

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

FIGURE 1–13

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



(a) Energy diagram

(b) Bonding diagram

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

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

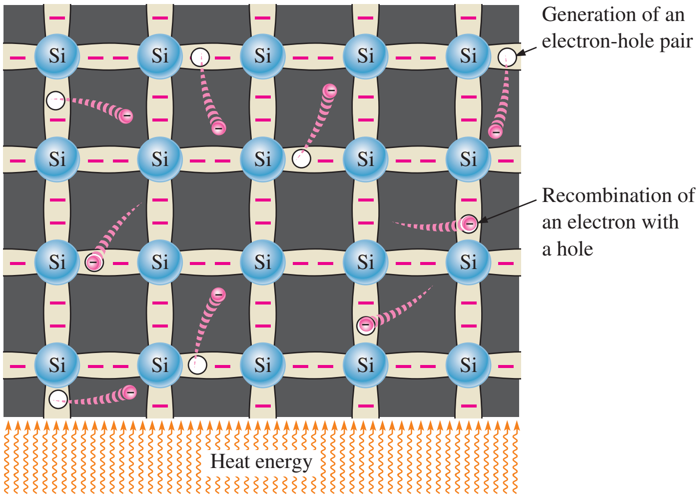


FIGURE 1–14

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

Electron and Hole Current

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

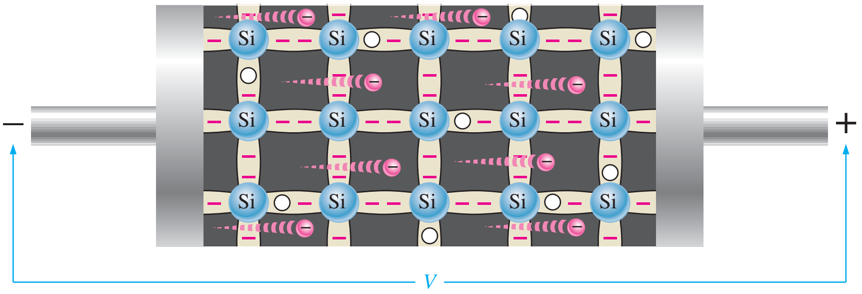


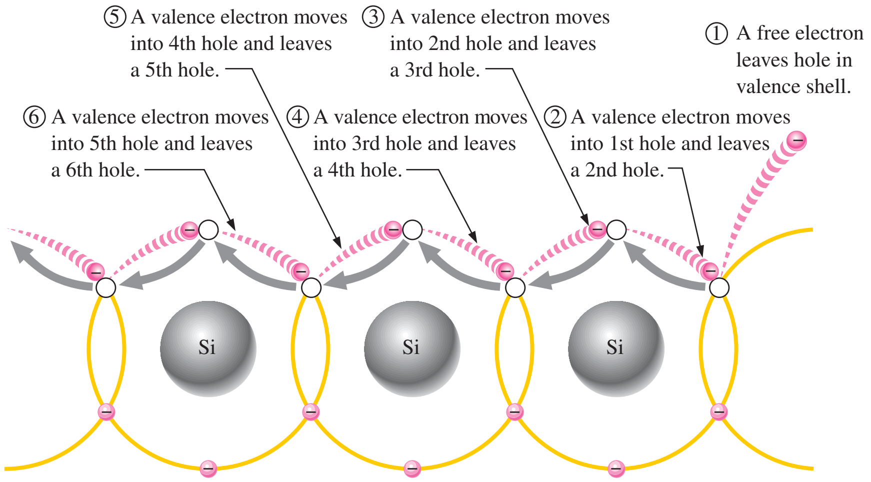
FIGURE 1–15

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

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

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

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



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.

▶ FIGURE 1–16

Hole current in intrinsic silicon.

SECTION 1–3 CHECKUP

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

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

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

After completing this section, you should be able to

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

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

N-Type Semiconductor

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

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

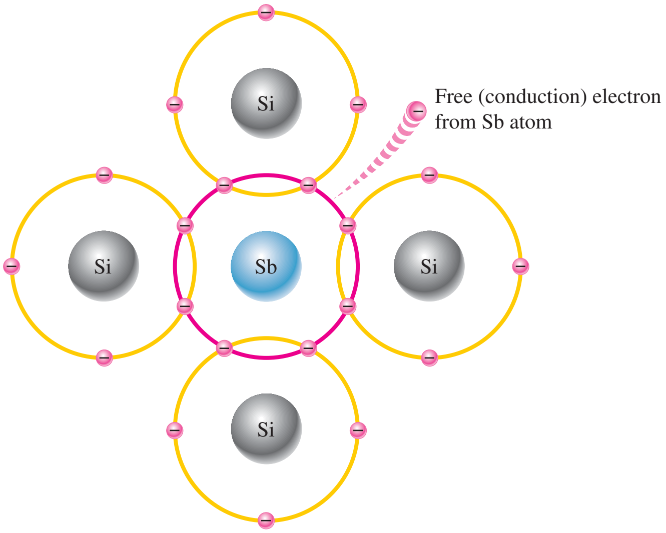


FIGURE 1–17

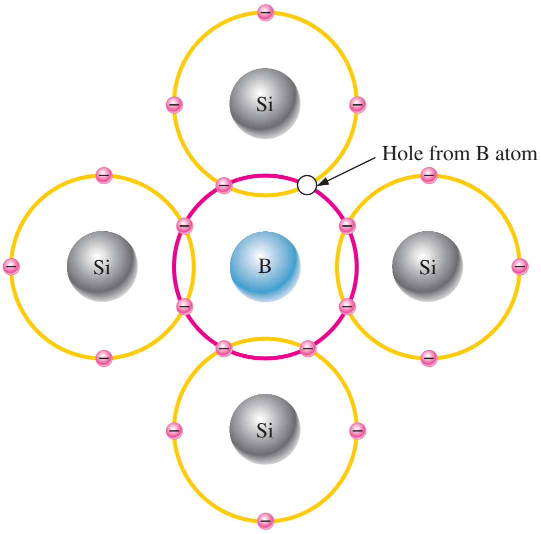
Pentavalent impurity atom in a silicon crystal structure. An antimony (Sb) impurity atom is shown in the center. The extra electron from the Sb atom becomes a free electron.

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

P-Type Semiconductor

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

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



▶ **FIGURE 1–18**

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

SECTION 1–4 CHECKUP

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

1–5 THE *PN* JUNCTION

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

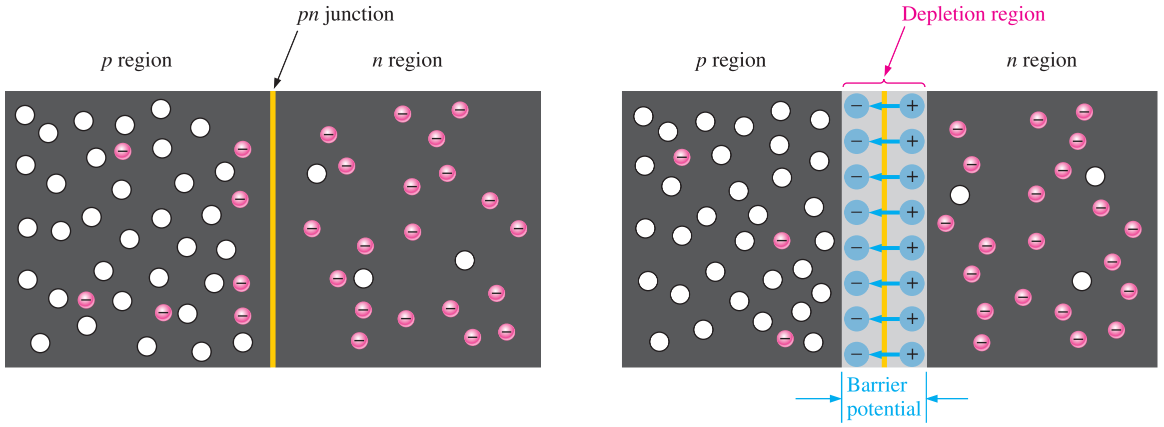
After completing this section, you should be able to

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

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

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

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



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

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

▲ **FIGURE 1–19**

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

Formation of the Depletion Region

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

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

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

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

HISTORY NOTE

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

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

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.

HISTORY NOTE

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

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

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

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

Energy Diagrams of the *PN* Junction and Depletion Region

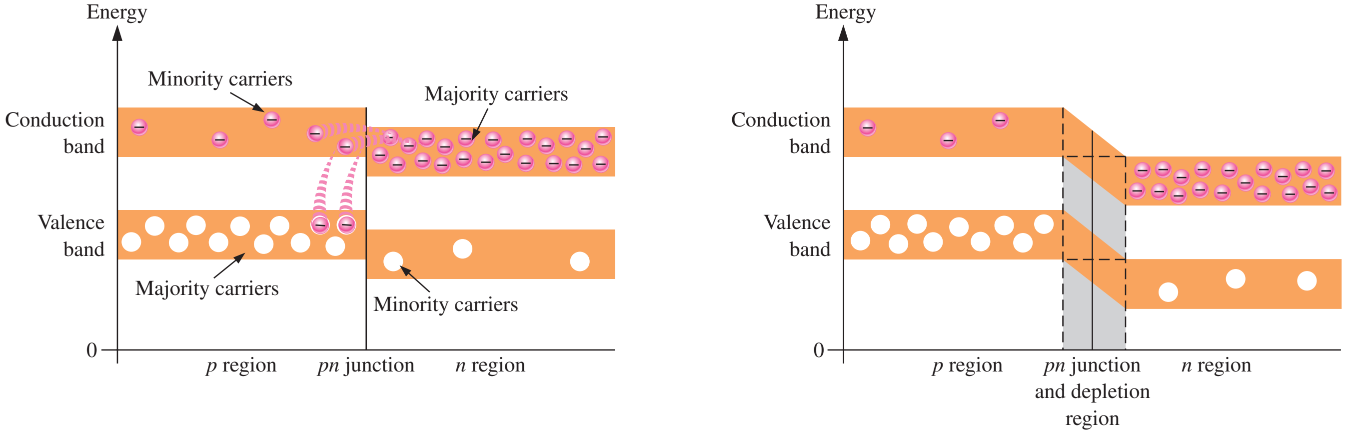
The valence and conduction bands in an *n*-type material are at slightly lower energy levels than the valence and conduction bands in a *p*-type material. Recall that *p*-type material has trivalent impurities and *n*-type material has pentavalent impurities. The trivalent impurities exert lower forces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

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

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

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

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



(a) At the instant of junction formation

(b) At equilibrium

▲ **FIGURE 1–20**

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

SECTION 1–5 CHECKUP

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

SUMMARY

Section 1–1

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

Section 1–2

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

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

Section 1–3

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

Section 1–4

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

Section 1–5

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

KEY TERMS

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

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

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

Conductor A material that easily conducts electrical current.

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

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

Electron The basic particle of negative electrical charge.

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

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

Insulator A material that does not normally conduct current.

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

Orbital Subshell in the quantum model of an atom.

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

Proton The basic particle of positive charge.

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

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

Silicon A semiconductive material.

Valence Related to the outer shell of an atom.

KEY FORMULA

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

TRUE/FALSE QUIZ

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

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

SELF-TEST

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

Section 1–1

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

Section 1–2

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

9. In a semiconductor crystal, the atoms are held together by

(a) the interaction of valence electrons **(b)** forces of attraction

(c) covalent bonds **(d)** answers (a), (b), and (c)

10. The atomic number of silicon is

(a) 8 **(b)** 2 **(c)** 4 **(d)** 14

11. The atomic number of germanium is

(a) 8 **(b)** 2 **(c)** 4 **(d)** 32

12. The valence shell in a silicon atom has the number designation of

(a) 0 **(b)** 1 **(c)** 2 **(d)** 3

13. Each atom in a silicon crystal has

(a) four valence electrons

(b) four conduction electrons

(c) eight valence electrons, four of its own and four shared

(d) no valence electrons because all are shared with other atoms

Section 1–3

14. Electron-hole pairs are produced by

(a) recombination **(b)** thermal energy **(c)** ionization **(d)** doping

15. Recombination is when

(a) an electron falls into a hole

(b) a positive and a negative ion bond together

(c) a valence electron becomes a conduction electron

(d) a crystal is formed

16. The current in a semiconductor is produced by

(a) electrons only **(b)** holes only **(c)** negative ions **(d)** both electrons and holes

Section 1–4

17. In an intrinsic semiconductor,

(a) there are no free electrons

(b) the free electrons are thermally produced

(c) there are only holes

(d) there are as many electrons as there are holes

(e) answers (b) and (d)

18. The process of adding an impurity to an intrinsic semiconductor is called

(a) doping **(b)** recombination **(c)** atomic modification **(d)** ionization

19. A trivalent impurity is added to silicon to create

(a) germanium **(b)** a *p*-type semiconductor

(c) an *n*-type semiconductor **(d)** a depletion region

20. The purpose of a pentavalent impurity is to

(a) reduce the conductivity of silicon **(b)** increase the number of holes

(c) increase the number of free electrons **(d)** create minority carriers

21. The majority carriers in an *n*-type semiconductor are

(a) holes **(b)** valence electrons **(c)** conduction electrons **(d)** protons

22. Holes in an *n*-type semiconductor are

(a) minority carriers that are thermally produced

(b) minority carriers that are produced by doping

(c) majority carriers that are thermally produced

(d) majority carriers that are produced by doping

Section 1–5

23. A *pn* junction is formed by

(a) the recombination of electrons and holes

(b) ionization

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

24. The depletion region is created by

(a) ionization **(b)** diffusion **(c)** recombination **(d)** answers (a), (b), and (c)

25. The depletion region consists of

- **(a)** nothing but minority carriers
- **(b)** positive and negative ions
- **(c)** no majority carriers
- **(d)** answers (b) and (c)

PROBLEMS

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

BASIC PROBLEMS

Section 1–1 The Atom

1. If the atomic number of a neutral atom is 6, how many electrons does the atom have? How many protons?

2. What is the maximum number of electrons that can exist in the 3rd shell of an atom?

Section 1–2 Materials Used in Electronics

3. For each of the energy diagrams in Figure 1–21, determine the class of material based on relative comparisons.

4. A certain atom has four valence electrons. What type of atom is it?

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

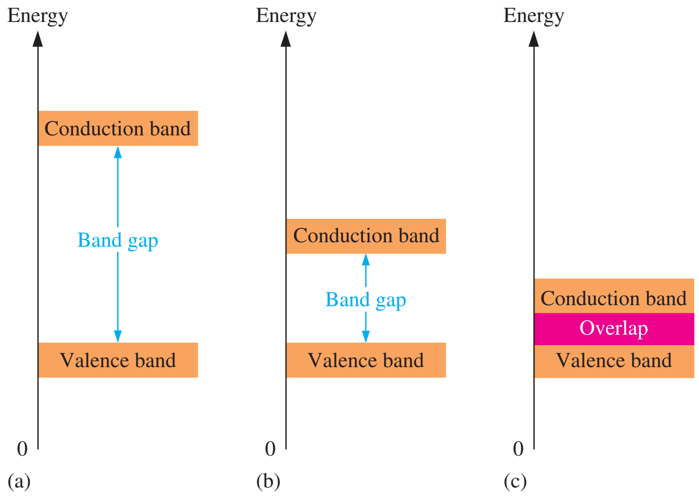


FIGURE 1–21

Section 1–3 Current in Semiconductors

6. What happens when heat is added to silicon?

7. Name the two energy bands at which current is produced in silicon.

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

8. Describe the process of doping and explain how it alters the atomic structure of silicon.

9. What is antimony? What is boron?

Section 1–5 The *PN* Junction

10. How is the electric field across the *pn* junction created?

11. Because of its barrier potential, can a diode be used as a voltage source? Explain.

GreenTech Application 1: *Solar Power*

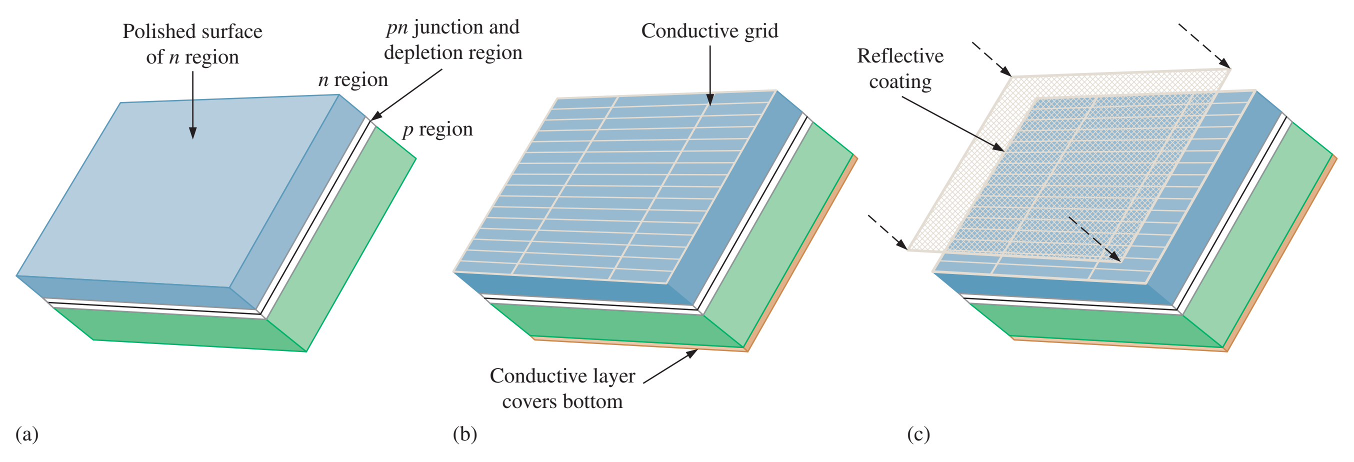
Photovoltaic (PV) Cell Structure and Operation

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

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

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

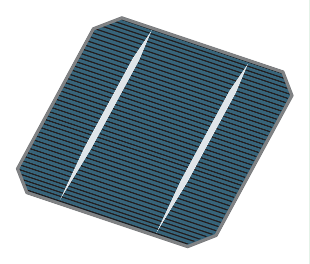
A grid-work of very thin conductive contact strips are deposited on top of the wafer by methods such as photoresist or silk-screen, as shown in part (b). The contact grid must maximize the surface area of the silicon wafer that be exposed to the sunlight in order to collect as much light energy as possible.



▲ FIGURE GA1–1

Basic construction of a PV solar cell.

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



▲ **FIGURE GA1–2**

A complete PV solar cell.

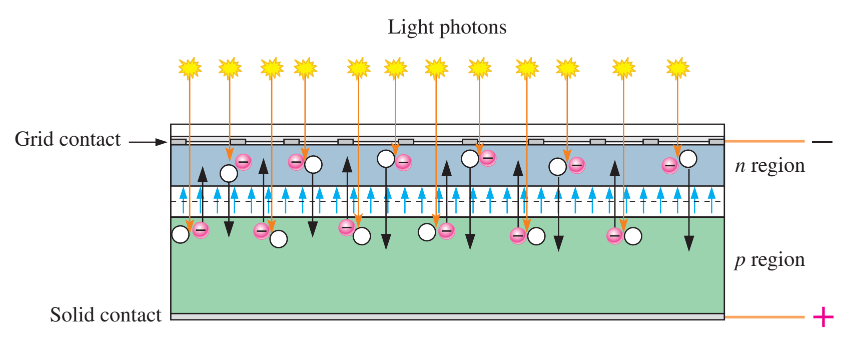
After the contacts are incorporated, an antireflective coating is placed on top the contact grid and *n* region, as shown in Figure GA1–1(c). This allows the solar cell to absorb as much of the sun's energy as possible by reducing the amount of light energy reflected away from the surface of the cell.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

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

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

▶ **FIGURE GA1–3**

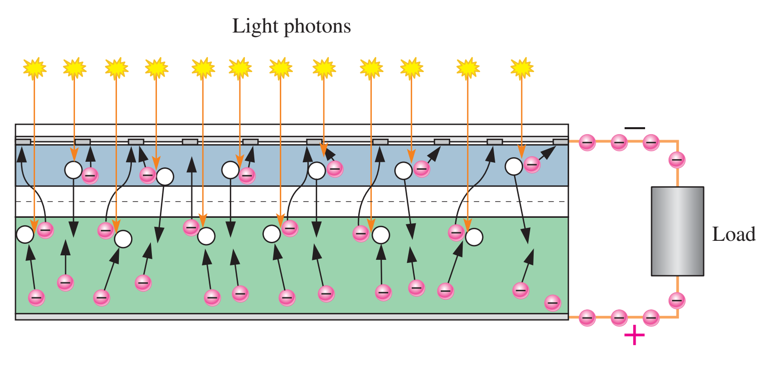
Basic operation of a solar cell with incident sunlight.



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

▶ **FIGURE GA1–4**

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



Solar Cell Characteristics

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

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

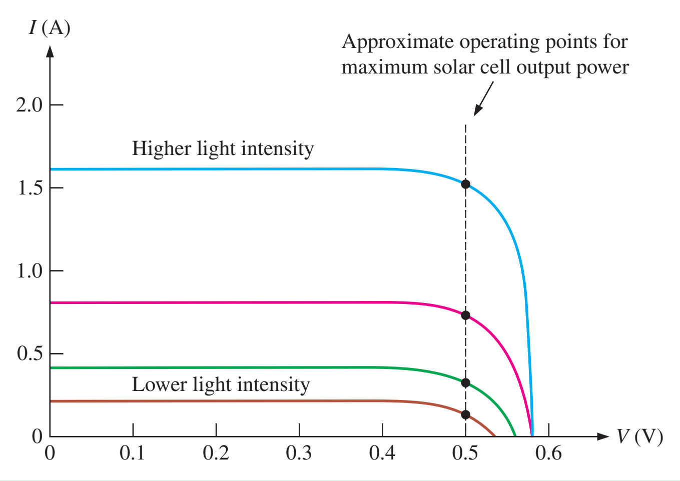


FIGURE GA1–5

V-I characteristic for a typical single solar cell from increasing light intensities.

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

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

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

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

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

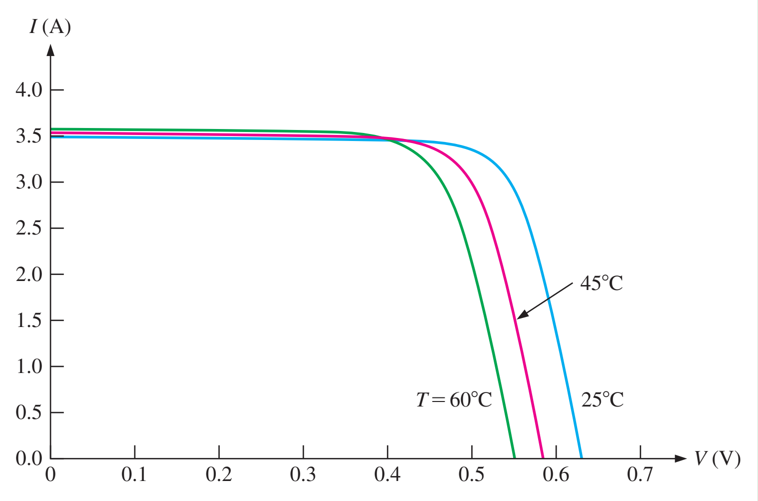
$$V = IR = (0.8\ \text{A})(0.33\ \text{W}) = 0.264\ \text{V}$$

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

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

FIGURE GA1–6

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



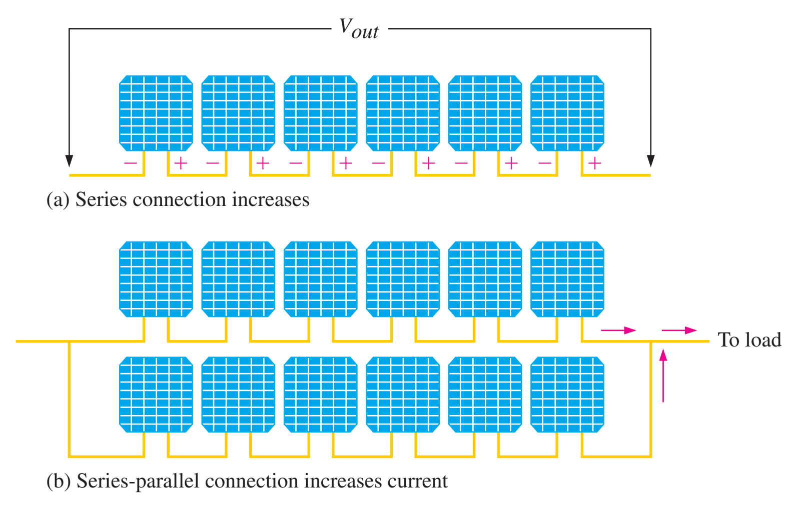
Solar Cell Panels

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

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

FIGURE GA1–7

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



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

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

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

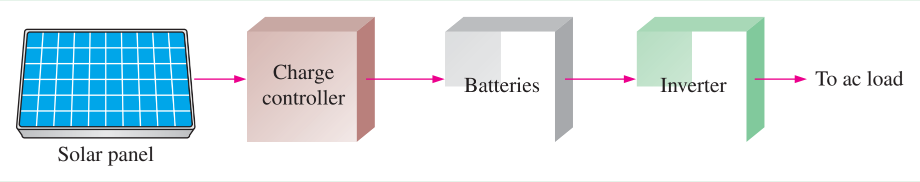
▲ FIGURE GA1–8

Large array of solar panels.

The Solar Power System

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

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



◀ FIGURE GA1–9

Basic solar power system with battery backup.

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

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

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

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

QUESTIONS

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

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

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

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

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

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

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

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