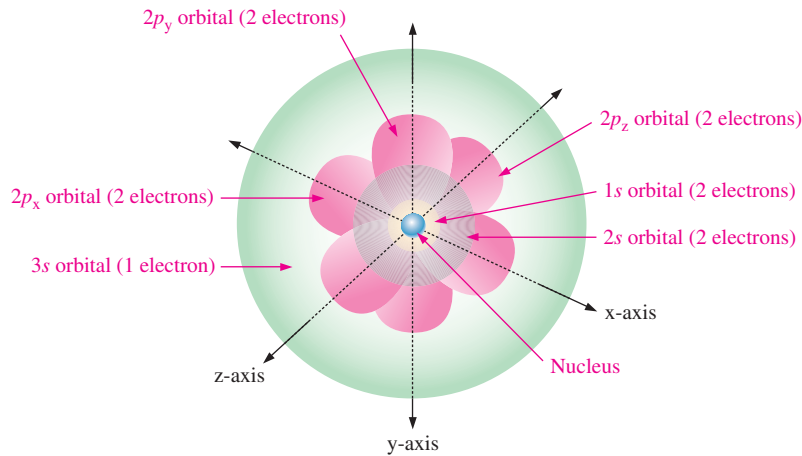


p -orbitals in each energy level are oriented at right angles to each other. One is oriented on the x -axis, one on the y -axis, and one on the z -axis. For example, a view of the quantum model of a sodium atom (Na) that has 11 electrons is shown in Figure 1–5. The three axes are shown to give you a 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.

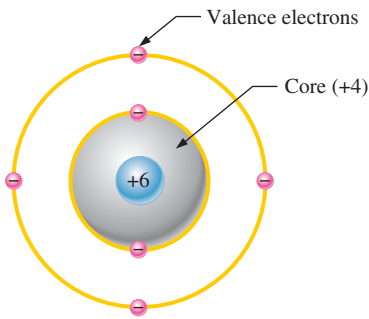
1. Describe the Bohr model of the atom.
2. Define *electron*.
3. What is the nucleus of an atom composed of? Define each component.
4. Define *atomic number*.
5. Discuss electron shells and orbits and their energy levels.
6. What is a valence electron?
7. What is a free electron?
8. Discuss the difference 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 germanium atoms
- Explain covalent bonds
 - ♦ Define *crystal*



▲ **FIGURE 1-6**
Diagram of a carbon atom.

Insulators, Conductors, and Semiconductors

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

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

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

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

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

Band Gap

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

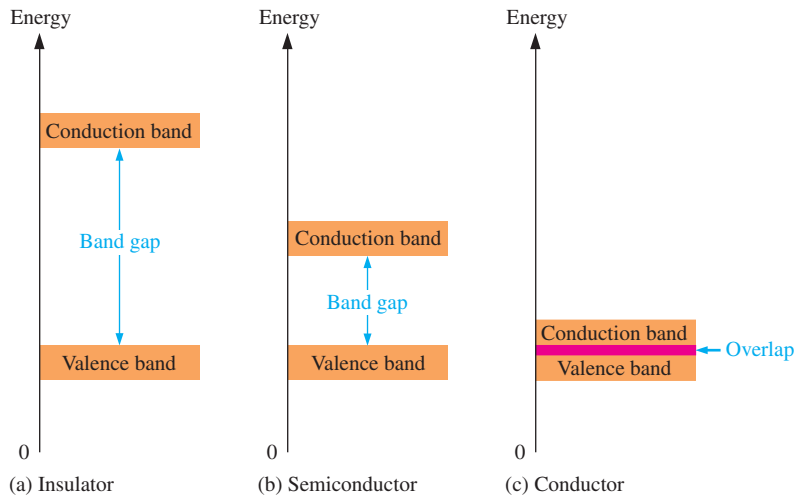
The difference in energy between the valence band and the conduction band is called an *energy gap* or **band gap**. This is the amount of energy that a valence electron must have in order to jump from the valence band to the conduction band. Once in the conduction band, the electron is free to move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

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

F Y I

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

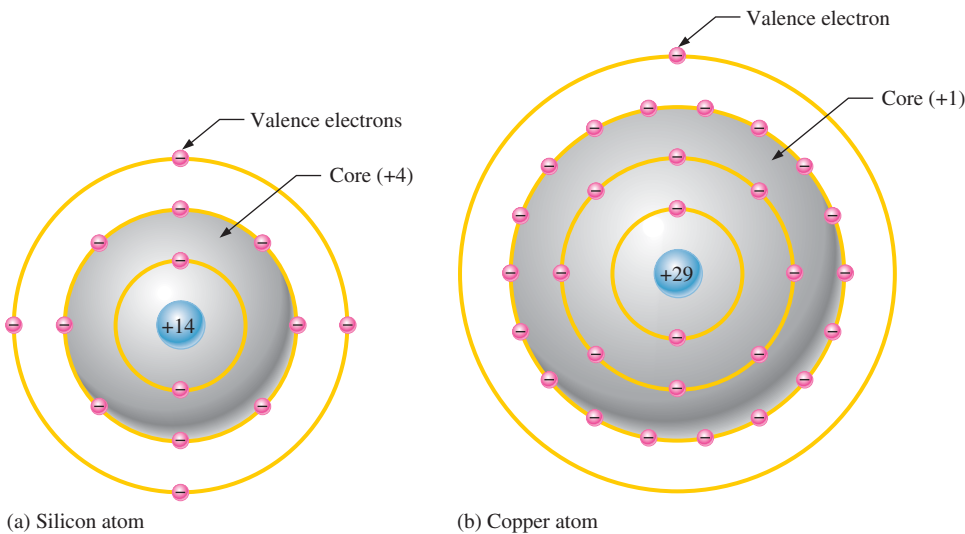
GaAs has the advantage of making semiconductor devices that respond very quickly to electrical signals. This makes it better than silicon for applications like amplifying the high frequency (1 GHz to 10 GHz) signals from TV satellites, etc. The main disadvantage of GaAs is that it is more difficult to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



◀ **FIGURE 1-7**
Energy diagrams for the three types of materials.

Comparison of a Semiconductor Atom to a Conductor Atom

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



◀ **FIGURE 1-8**
Bohr diagrams of the silicon and copper atoms.

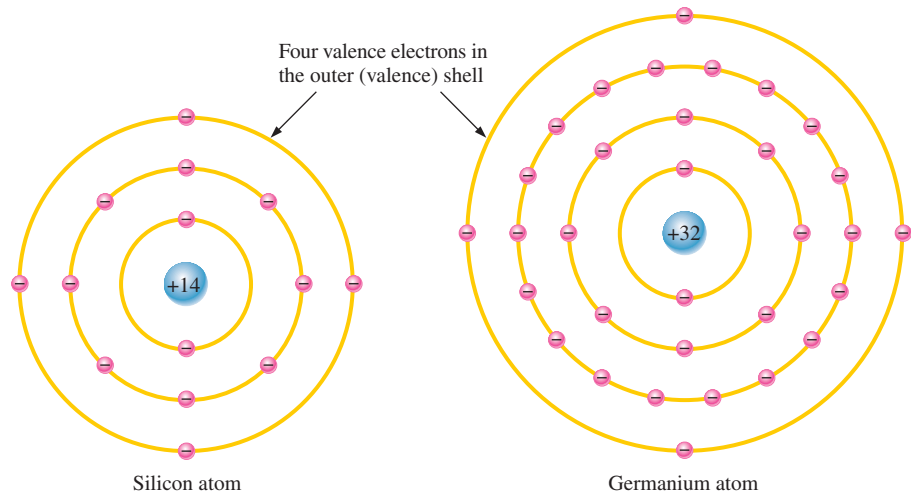
The valence electron in the copper atom “feels” an attractive force of +1 compared to a valence electron in the silicon atom which “feels” an attractive force of +4. Therefore, there is more force trying to hold a valence electron to the atom in silicon than in copper. The copper’s valence electron is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

Silicon and Germanium

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

► **FIGURE 1-9**

Diagrams of the silicon and germanium atoms.

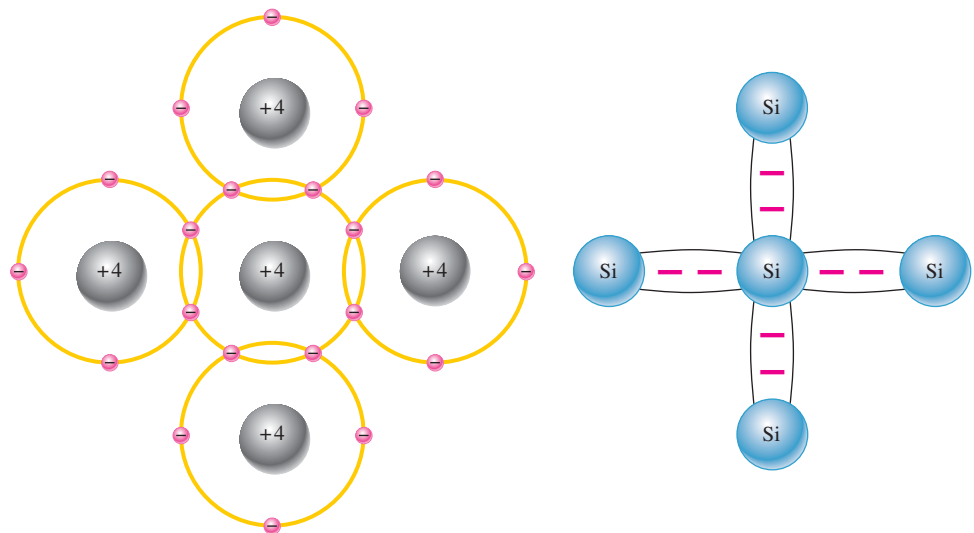


The valence electrons in germanium are in the fourth shell while those in silicon are in the third shell, closer to the nucleus. This means that the germanium valence electrons are at higher energy levels than those in silicon and, therefore, require a smaller amount of additional energy to escape from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

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

► **FIGURE 1-10**

Illustration of covalent bonds in silicon.



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

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