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

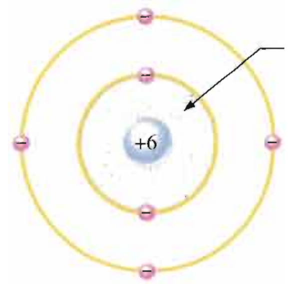
- **Discuss semiconductors, conductors, and insulators and how they basically differ**
- Define the core of an atom
- Describe the atomic structure of copper, silicon, germanium, and carbon
- List the four best conductors
- List four semiconductors
- Discuss the difference between conductors and semiconductors
- 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.

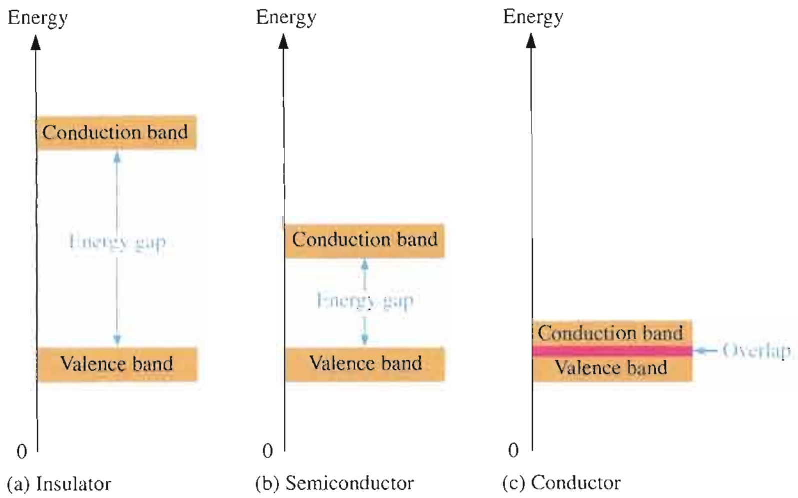


FIGURE 1–5

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.

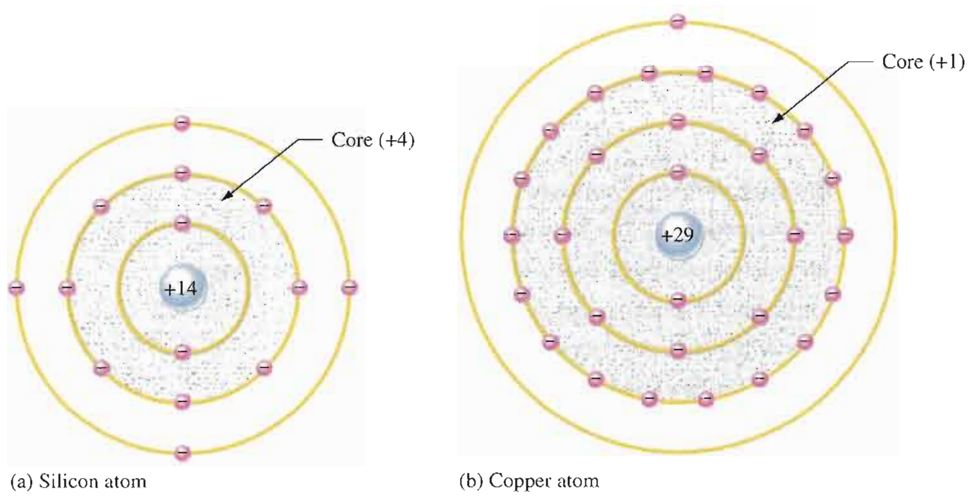


FIGURE 1–6

Diagrams of the silicon and copper atoms.

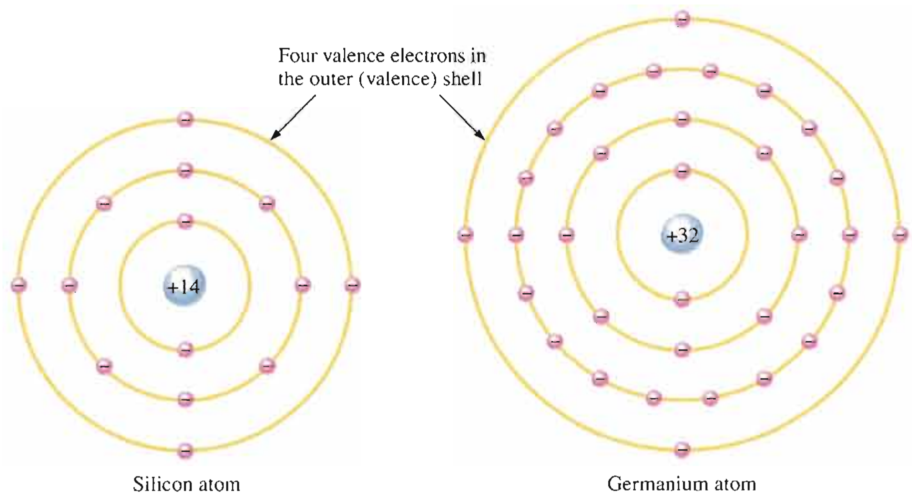
The valence electron in the copper atom "feels" an attractive force of +1 compared to a valence electron in the silicon atom which "feels" an attractive force of +4. Therefore, there is four times more force trying to hold a valence electron to the atom in silicon than in copper. The copper's valence 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

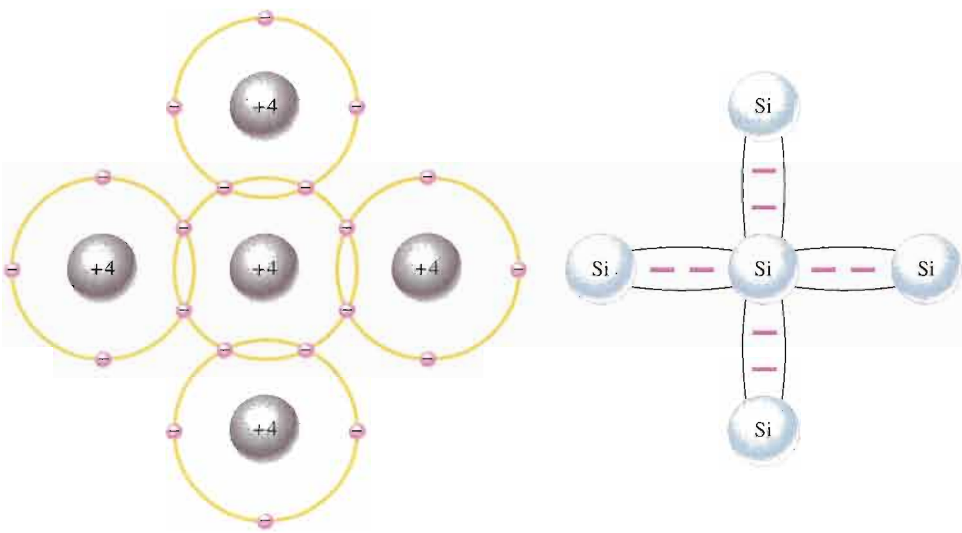
When atoms combine to form a solid, crystalline material, they arrange themselves in a symmetrical pattern. The atoms within the crystal structure are held together by covalent bonds, which are created by the interaction of the valence electrons of the atoms. Silicon is a crystalline material.

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.

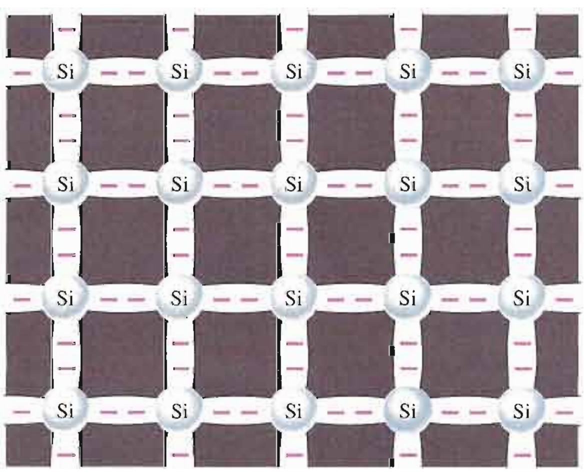


FIGURE 1–9

Covalent bonds in a silicon crystal.