SEMICONDUCTOR BASICS

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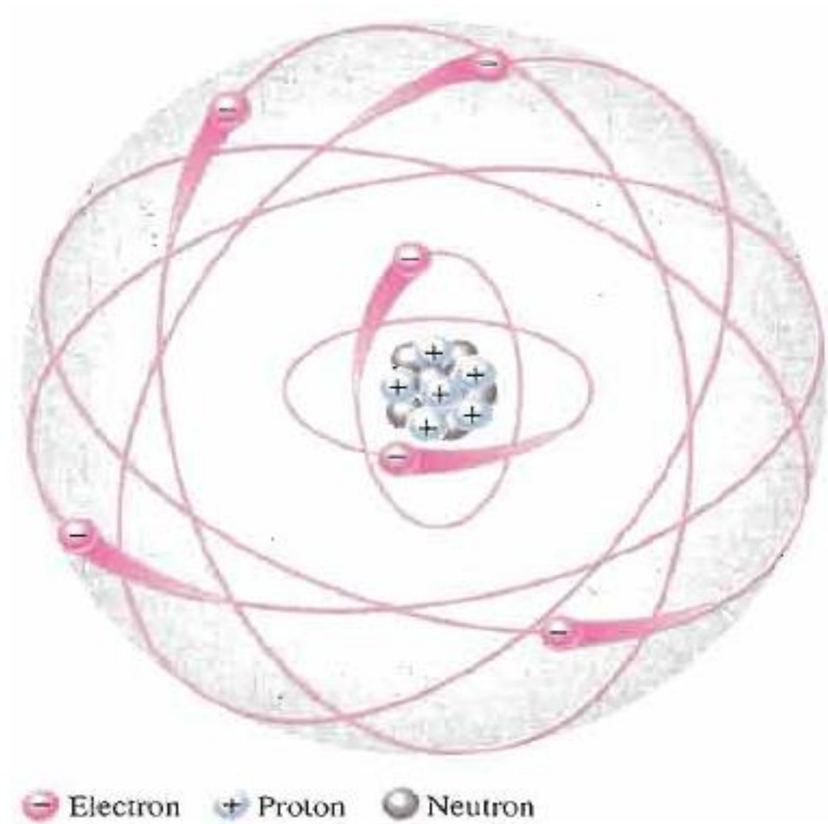
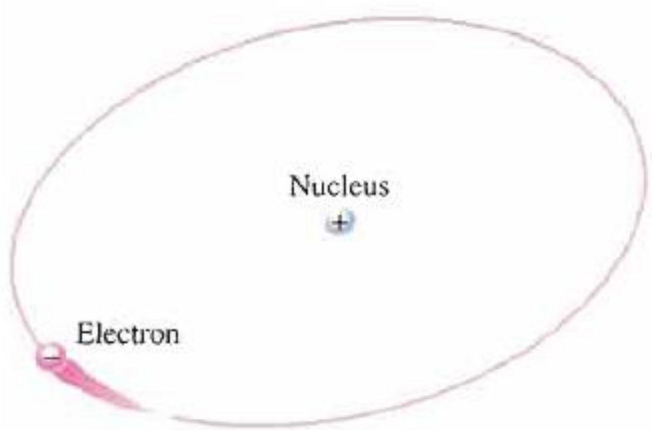
Atomic Structure

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

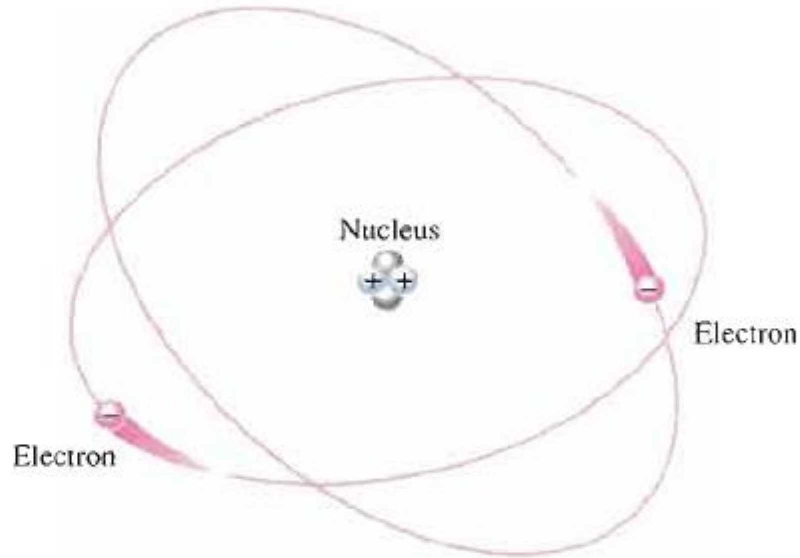
FIGURE 1–1

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



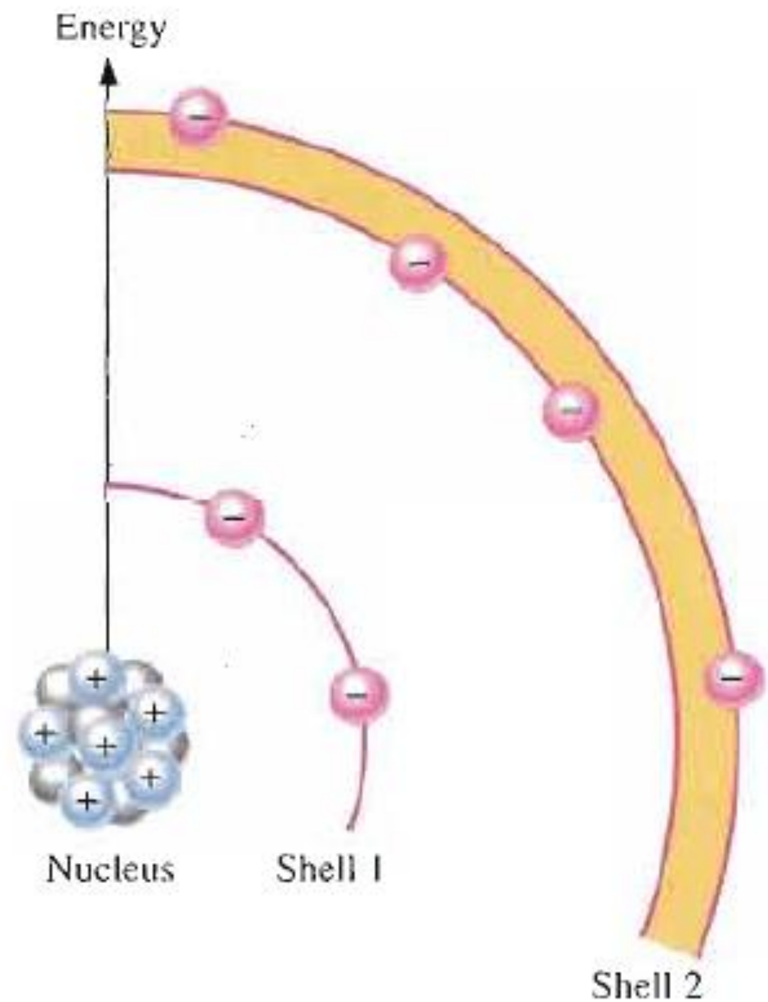
(b) Helium atom

Electron Shells and Orbits

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

FIGURE 1–3

Energy increases as the distance from the nucleus increases.



The Number of Electrons in Each Shell

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

$$N_e = 2n^2$$

where n is the number of the shell. The innermost shell is number 1, the next shell is number 2, and so on. The maximum number of electrons that can exist in the innermost shell (shell 1) is

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

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

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

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

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

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

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

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

Semiconductors, Conductors and Insulators

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**.

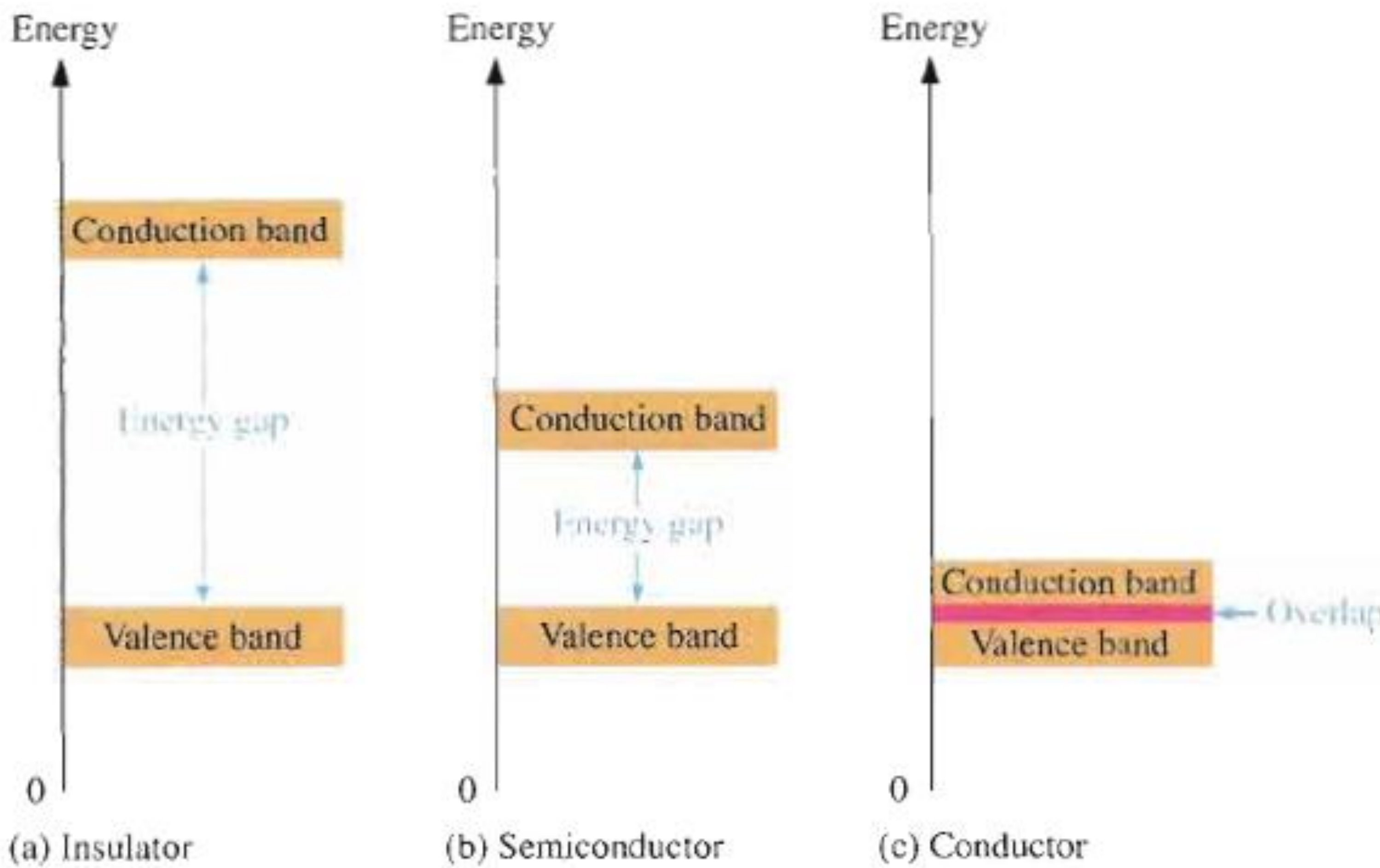
Insulators

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

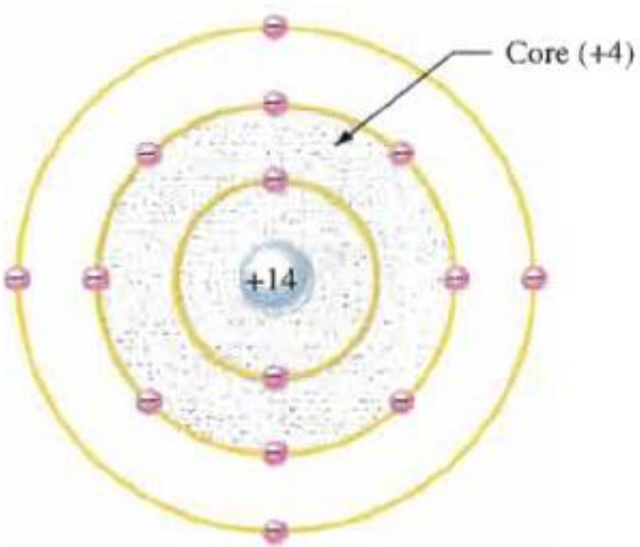
A **semiconductor** is a material that is between conductors and insulators in its ability to conduct electrical current. A semiconductor in its pure (intrinsic) state is neither a good conductor nor a good insulator. The most common single-element semiconductors are **silicon**, **germanium**, and **carbon**. Compound semiconductors such as gallium arsenide are also commonly used. The single-element semiconductors are characterized by atoms with four valence electrons.

Energy Bands

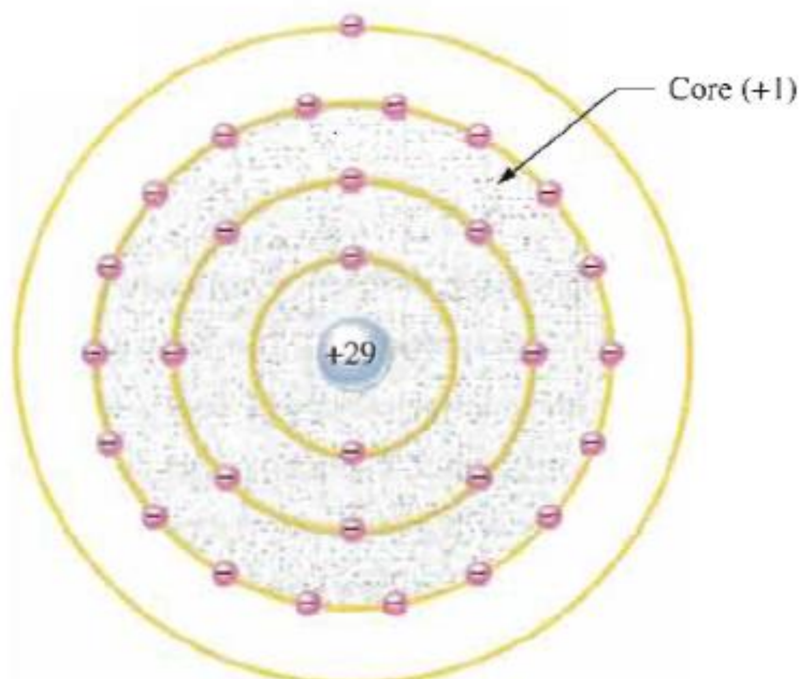


Comparison of a Semiconductor Atom to a Conductor Atom

Silicon is a semiconductor and copper is a conductor. Diagrams of the silicon atom and the copper atom are shown in Figure 1–6. Notice that the core of the silicon atom has a net charge of +4 (14 protons − 10 electrons) and the core of the copper atom has a net charge of +1 (29 protons − 28 electrons). The core is everything except the valence electrons.



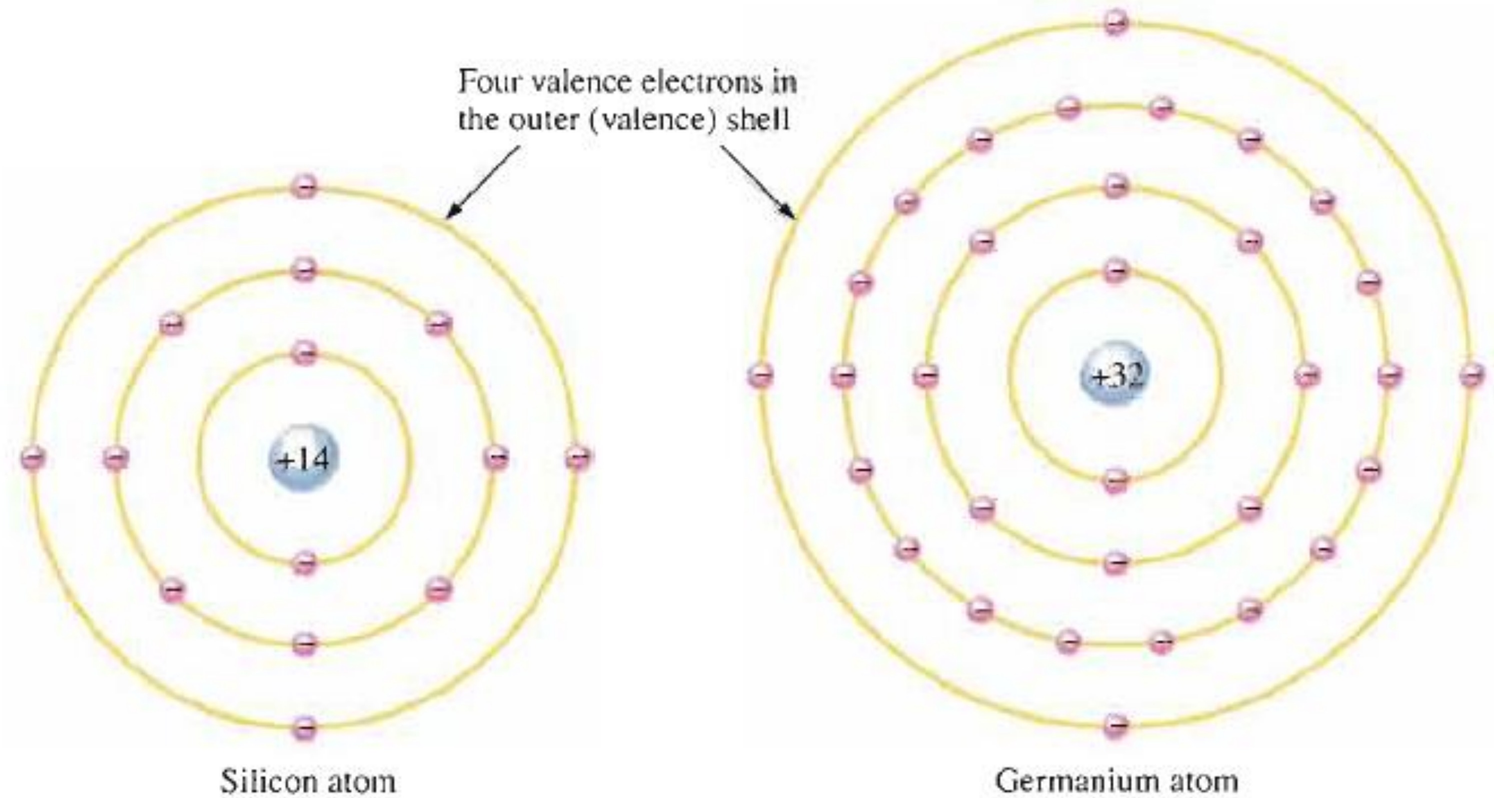
(a) Silicon atom



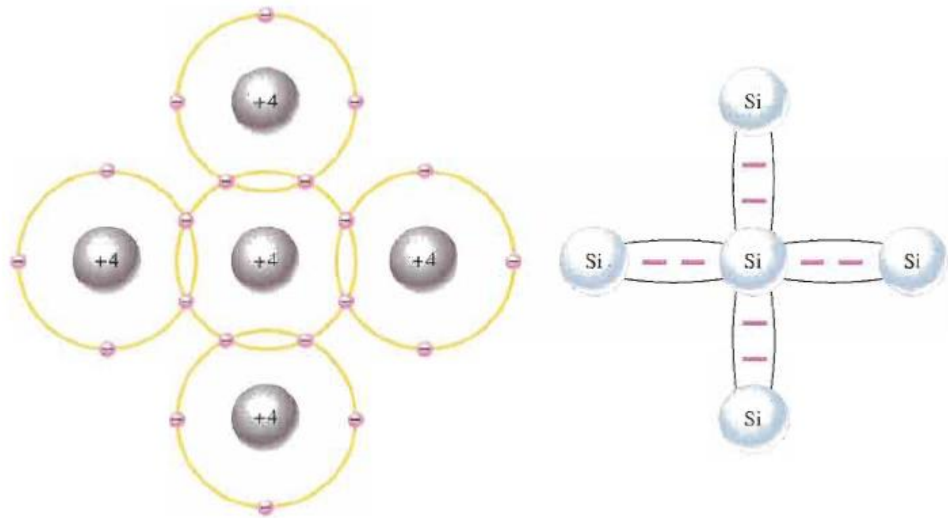
(b) Copper atom

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.



Covalent Bonds



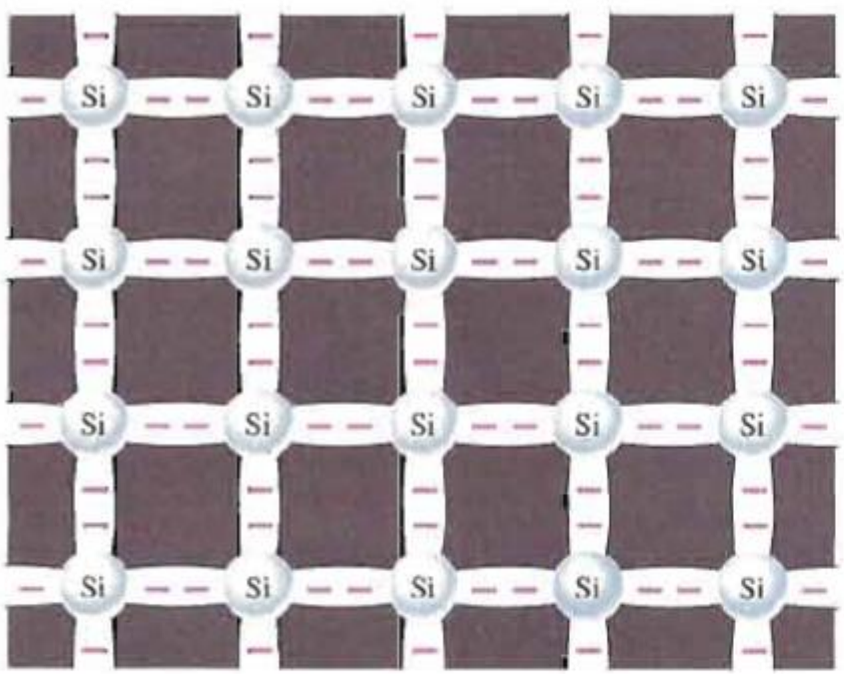


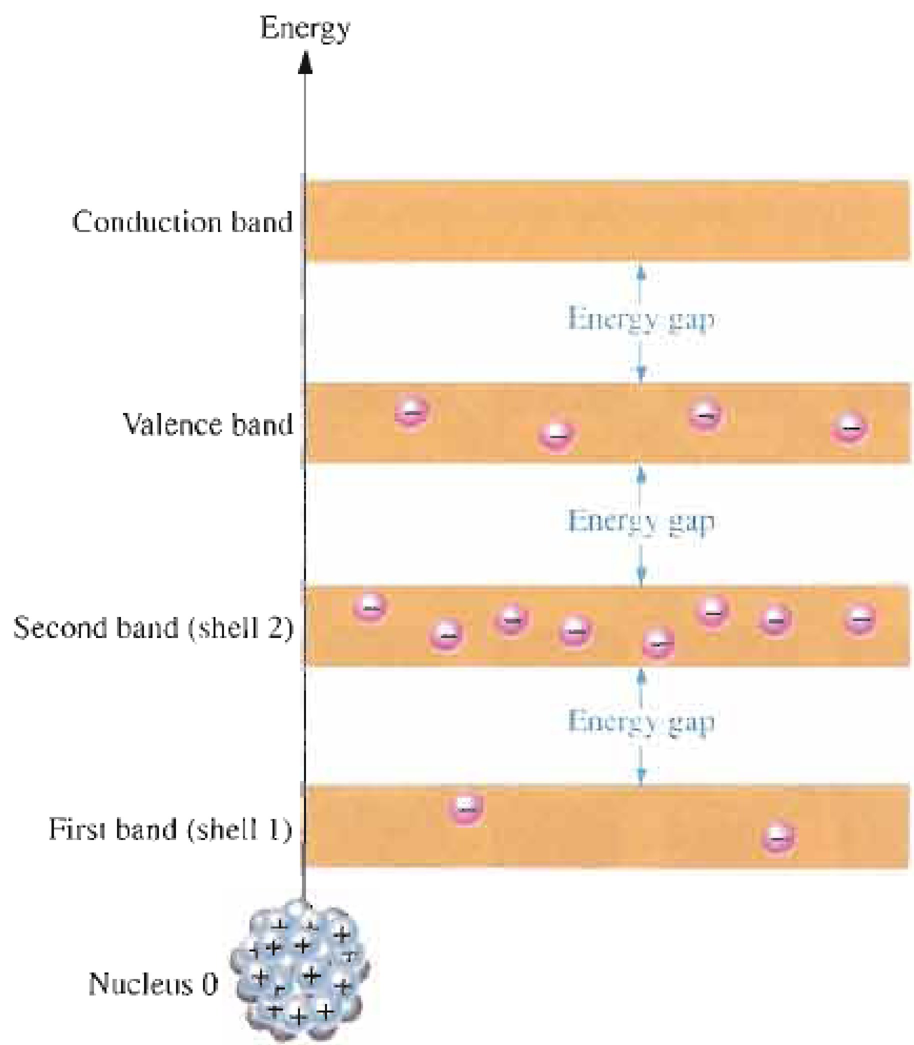
FIGURE 1–9

Covalent bonds in a silicon crystal.

Conduction in Semiconductors

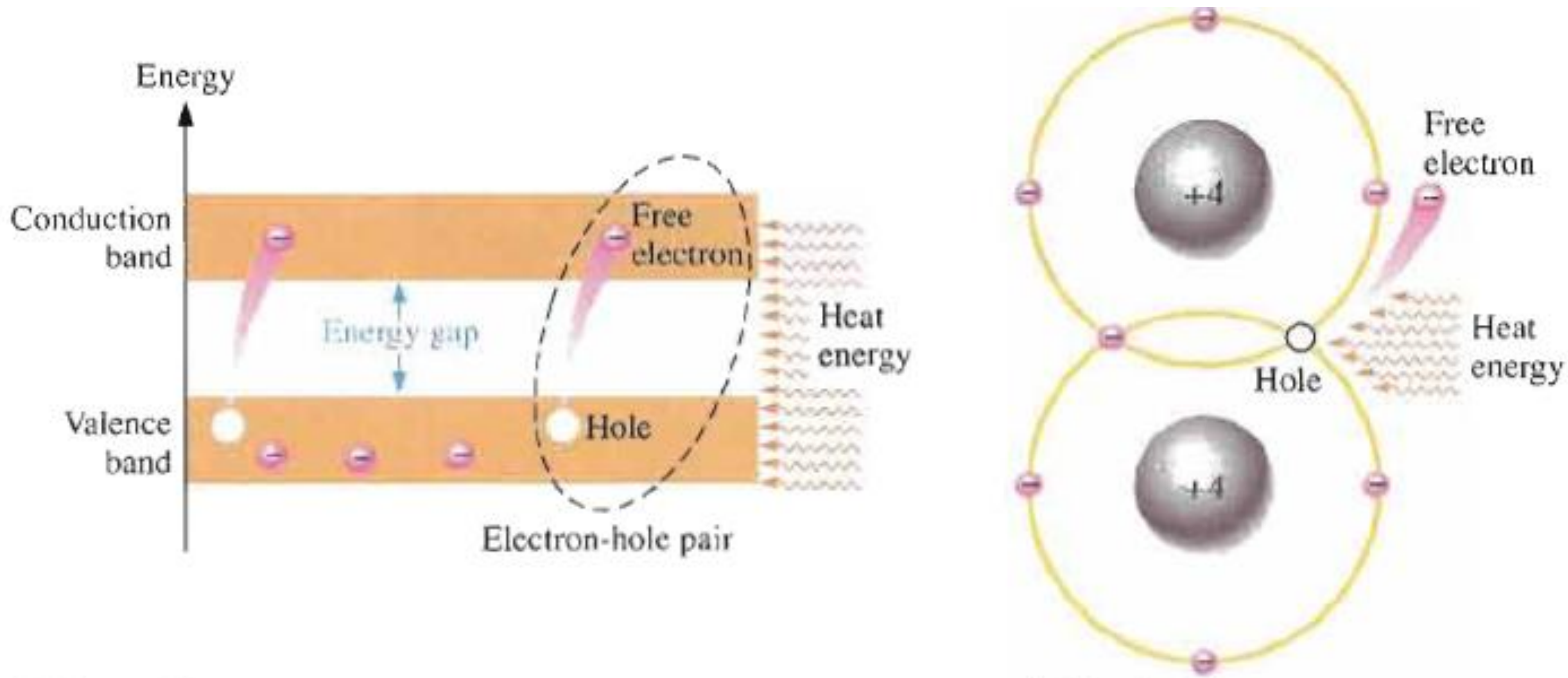
FIGURE 1–10

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



Conduction Electrons and Holes

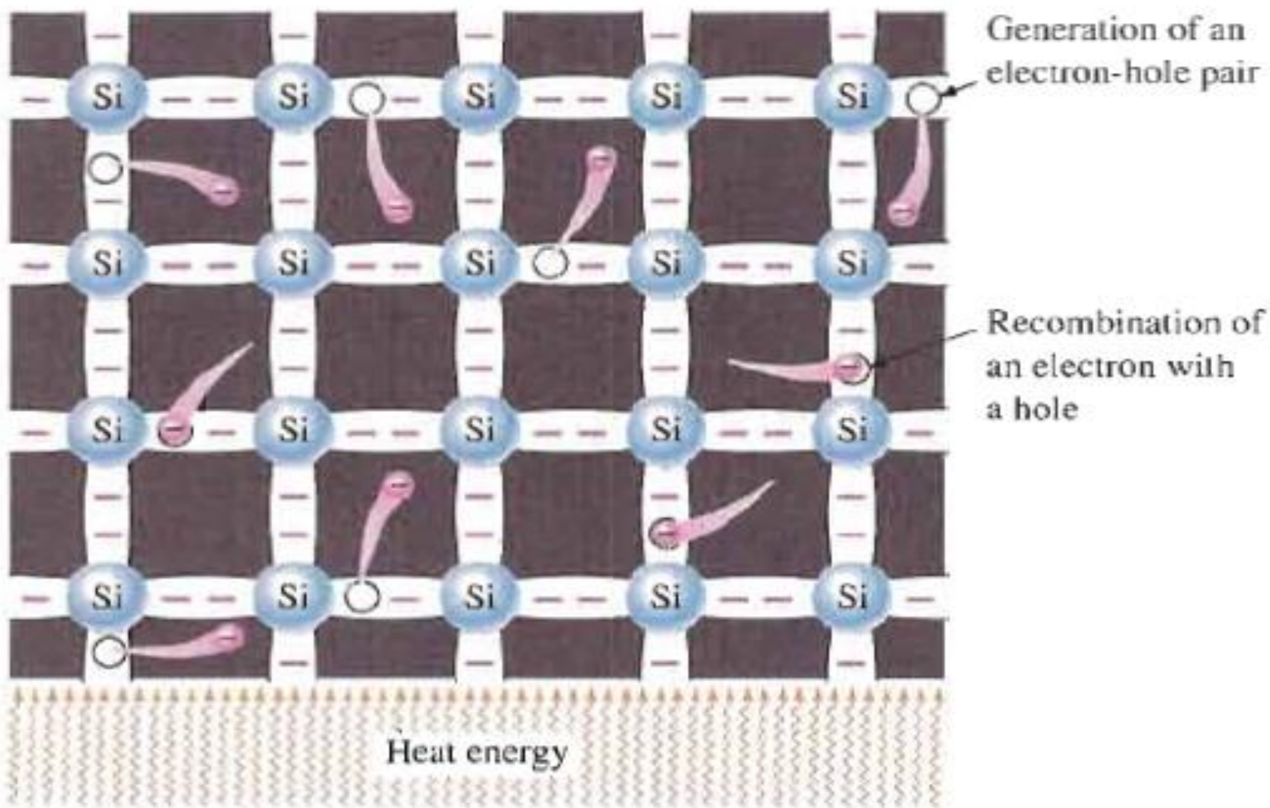
An intrinsic (pure) silicon crystal at room temperature has sufficient heat (thermal) energy for some valence electrons to jump the gap from the valence band into the conduction band, becoming free electrons. Free electrons are also called **conduction electrons**. This is illustrated in the energy diagram of Figure 1–11(a) and in the bonding diagram of Figure 1–11(b).



(a) Energy diagram

(b) Bonding diagram

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.



DIODE THEORY AND APPLICATIONS

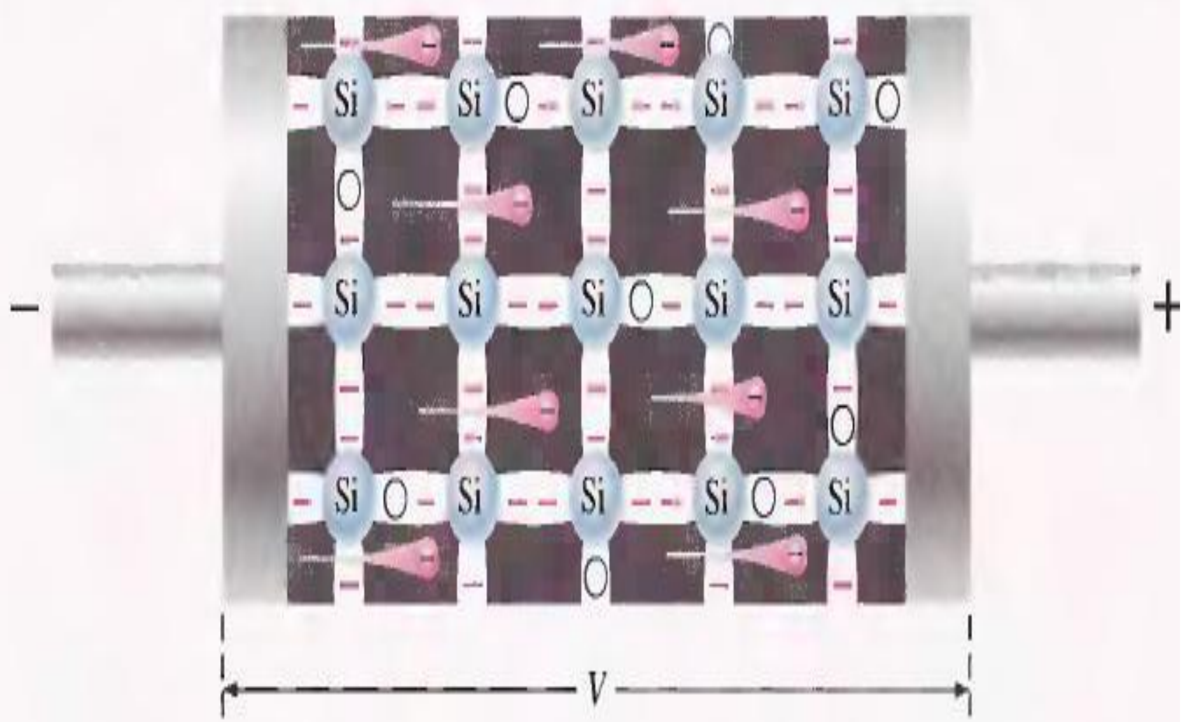
SEMICONDUCTOR DIODES:

What is an Intrinsic Semiconductor?

A pure semiconductor (Tetravalent elements) wafer in the absence of any impurities.

FIGURE 1-13

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



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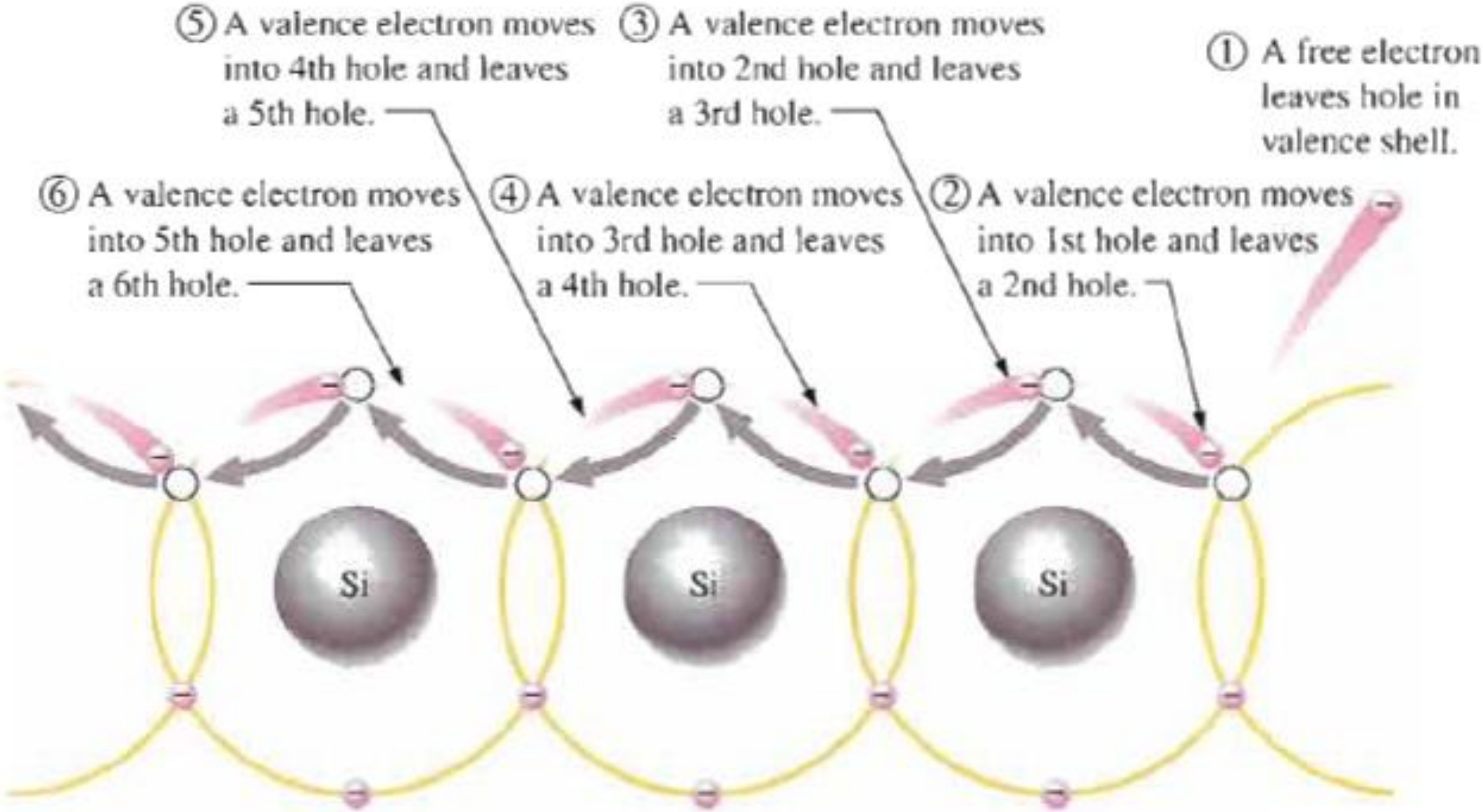


When a valence electron moves left to right to fill a hole while leaving another hole behind, the hole has effectively moved from right to left. Gray arrows indicate effective movement of a hole.

What is Doping?

Doping

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

N-Type Semiconductor:

It is produced by adding Pentavalent Impurity atoms in an Intrinsic semiconductor crystal.

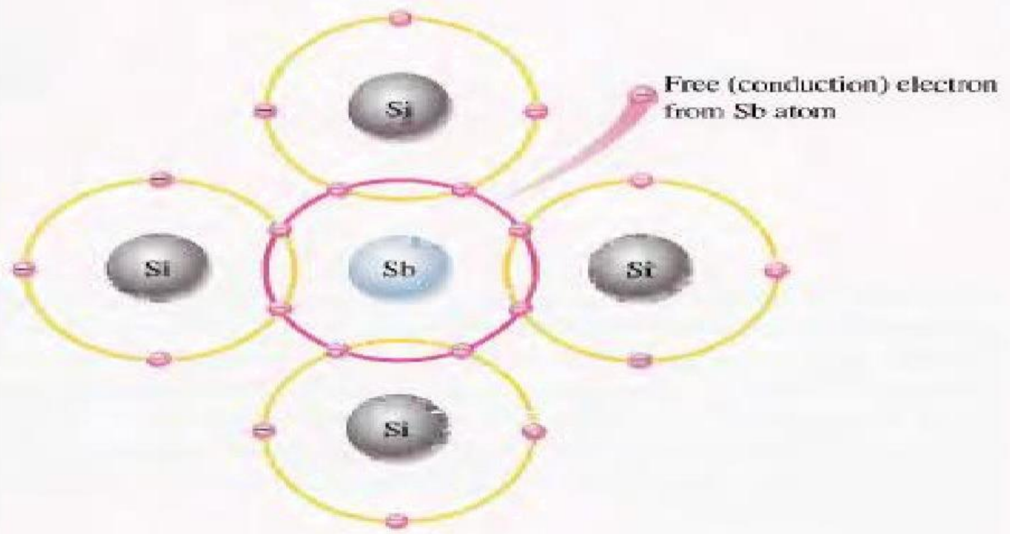


FIGURE 1–15

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

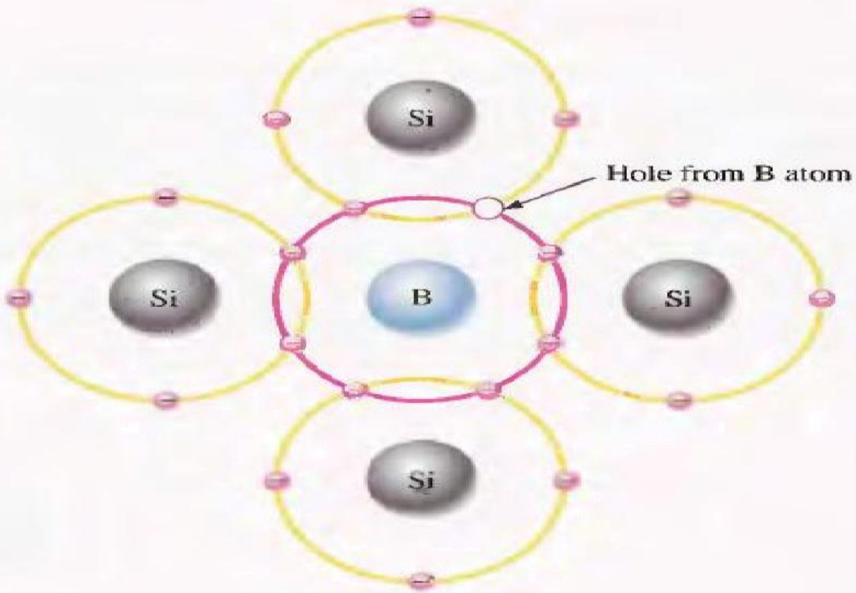
Majority and Minority Carriers Since most of the current carriers are electrons, silicon (or germanium) doped with pentavalent atoms is an *n*-type semiconductor (the *n* stands for the negative charge on an electron). The electrons are called the **majority carriers** in *n*-type material. Although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

It is produced by adding Trivalent Impurity atoms in an Intrinsic semiconductor crystal.

FIGURE 1–16

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



Majority and Minority Carriers Since most of the current carriers are holes, silicon (or germanium) doped with trivalent atoms is called a *p*-type semiconductor. Holes can be thought of as positive charges because the absence of an electron leaves a net positive charge on the atom. The holes are the majority carriers in *p*-type material. Although the majority of current carriers in *p*-type material are holes, there are also a few free electrons that are created when electron-hole pairs are thermally generated. These free electrons are *not* produced by the addition of the trivalent impurity atoms. Electrons in *p*-type material are the minority carriers.