

and flow of charge carriers in the semiconductor devices are *within the solid itself*, while in the earlier vacuum tubes/valves, the mobile electrons were obtained from a heated cathode and they were made to flow in an *evacuated* space or vacuum. No external heating or large evacuated space is required by the semiconductor devices. They are small in size, consume low power, operate at low voltages and have long life and high reliability. Even the Cathode Ray Tubes (CRT) used in television and computer monitors which work on the principle of vacuum tubes are being replaced by Liquid Crystal Display (LCD) monitors with supporting solid state electronics. Much before the full implications of the semiconductor devices was formally understood, a naturally occurring crystal of *galena* (Lead sulphide, PbS) with a metal point contact attached to it was used as *detector* of radio waves.

In the following sections, we will introduce the basic concepts of semiconductor physics and discuss some semiconductor devices like junction diodes (a 2-electrode device) and bipolar junction transistor (a 3-electrode device). A few circuits illustrating their applications will also be described.

## 14.2 CLASSIFICATION OF METALS, CONDUCTORS AND SEMICONDUCTORS

### On the basis of conductivity

On the basis of the relative values of electrical conductivity ( $\sigma$ ) or resistivity ( $\rho = 1/\sigma$ ), the solids are broadly classified as:

(i) **Metals:** They possess very low resistivity (or high conductivity).

$$\rho \sim 10^{-2} - 10^{-8} \Omega \text{ m}$$

$$\sigma \sim 10^2 - 10^8 \text{ S m}^{-1}$$

(ii) **Semiconductors:** They have resistivity or conductivity intermediate to metals and insulators.

$$\rho \sim 10^{-5} - 10^6 \Omega \text{ m}$$

$$\sigma \sim 10^5 - 10^{-6} \text{ S m}^{-1}$$

(iii) **Insulators:** They have high resistivity (or low conductivity).

$$\rho \sim 10^{11} - 10^{19} \Omega \text{ m}$$

$$\sigma \sim 10^{-11} - 10^{-19} \text{ S m}^{-1}$$

The values of  $\rho$  and  $\sigma$  given above are indicative of magnitude and could well go outside the ranges as well. Relative values of the resistivity are not the only criteria for distinguishing metals, insulators and semiconductors from each other. There are some other differences, which will become clear as we go along in this chapter.

Our interest in this chapter is in the study of semiconductors which could be:

- (i) *Elemental semiconductors:* Si and Ge
- (ii) *Compound semiconductors:* Examples are:
  - Inorganic: CdS, GaAs, CdSe, InP, etc.
  - Organic: anthracene, doped phthalocyanines, etc.
  - Organic polymers: polypyrrole, polyaniline, polythiophene, etc.

Most of the currently available semiconductor devices are based on elemental semiconductors Si or Ge and compound *inorganic*

semiconductors. However, after 1990, a few semiconductor devices using organic semiconductors and semiconducting polymers have been developed signalling the birth of a futuristic technology of polymer-electronics and molecular-electronics. In this chapter, we will restrict ourselves to the study of inorganic semiconductors, particularly elemental semiconductors Si and Ge. The general concepts introduced here for discussing the elemental semiconductors, by-and-large, apply to most of the compound semiconductors as well.

### On the basis of energy bands

According to the Bohr atomic model, in an *isolated atom* the energy of any of its electrons is decided by the orbit in which it revolves. But when the atoms come together to form a solid they are close to each other. So the outer orbits of electrons from neighbouring atoms would come very close or could even overlap. This would make the nature of electron motion in a solid very different from that in an isolated atom.

Inside the crystal each electron has a unique position and no two electrons see exactly the same pattern of surrounding charges. Because of this, each electron will have a different *energy level*. These different energy levels with continuous energy variation form what are called *energy bands*. The energy band which includes the energy levels of the valence electrons is called the *valence band*. The energy band above the valence band is called the *conduction band*. With no external energy, all the valence electrons will reside in the valence band. If the lowest level in the conduction band happens to be lower than the highest level of the valence band, the electrons from the valence band can easily move into the conduction band. Normally the conduction band is empty. But when it overlaps on the valence band electrons can move freely into it. This is the case with metallic conductors.

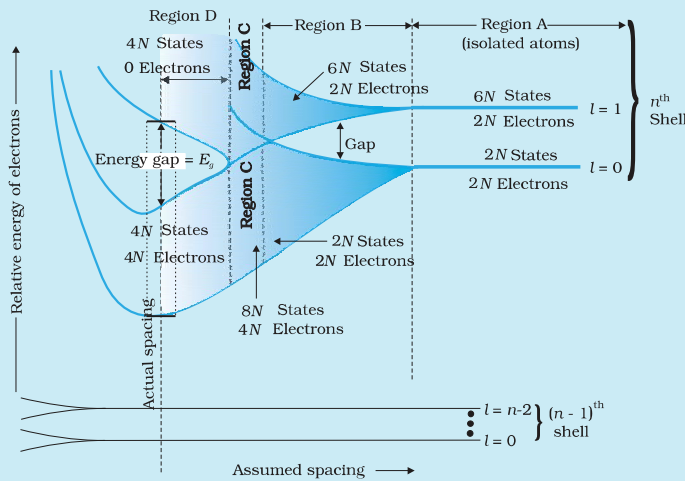
If there is some gap between the conduction band and the valence band, electrons in the valence band all remain bound and no free electrons are available in the conduction band. This makes the material an insulator. But some of the electrons from the valence band may gain external energy to cross the gap between the conduction band and the valence band. Then these electrons will move into the conduction band. At the same time they will create vacant energy levels in the valence band where other valence electrons can move. Thus the process creates the possibility of conduction due to electrons in conduction band as well as due to vacancies in the valence band.

Let us consider what happens in the case of Si or Ge crystal containing  $N$  atoms. For Si, the outermost orbit is the third orbit ( $n = 3$ ), while for Ge it is the fourth orbit ( $n = 4$ ). The number of electrons in the outermost orbit is 4 ( $2s$  and  $2p$  electrons). Hence, the total number of outer electrons in the crystal is  $4N$ . The maximum possible number of electrons in the outer orbit is 8 ( $2s + 6p$  electrons). So, for the  $4N$  valence electrons there are  $8N$  available energy states. These  $8N$  discrete energy levels can either form a continuous band or they may be grouped in different bands depending upon the distance between the atoms in the crystal (see box on Band Theory of Solids).

At the distance between the atoms in the crystal lattices of Si and Ge, the energy band of these  $8N$  states is split apart into two which are separated by an *energy gap*  $E_g$  (Fig. 14.1). The lower band which is

completely occupied by the  $4N$  valence electrons at temperature of absolute zero is the *valence band*. The other band consisting of  $4N$  energy states, called the *conduction band*, is completely empty at absolute zero.

### BAND THEORY OF SOLIDS



Consider that the Si or Ge crystal contains  $N$  atoms. Electrons of each atom will have discrete energies in different orbits. The electron energy will be same if all the atoms are *isolated*, i.e., separated from each other by a large distance. However, in a crystal, the atoms are close to each other (2 to 3 Å) and therefore the electrons interact with each other and also with the neighbouring atomic cores. The overlap (or interaction) will be more felt by the electrons in the outermost orbit while the inner orbit or core electron energies may

remain unaffected. Therefore, for understanding electron energies in Si or Ge crystal, we need to consider the changes in the energies of the electrons in the outermost orbit only. For Si, the outermost orbit is the third orbit ( $n = 3$ ), while for Ge it is the fourth orbit ( $n = 4$ ). The number of electrons in the outermost orbit is 4 ( $2s$  and  $2p$  electrons). Hence, the total number of outer electrons in the crystal is  $4N$ . The maximum possible number of outer electrons in the orbit is 8 ( $2s + 6p$  electrons). So, out of the  $4N$  electrons,  $2N$  electrons are in the  $2N$   $s$ -states (orbital quantum number  $l = 0$ ) and  $2N$  electrons are in the available  $6N$   $p$ -states. Obviously, some  $p$ -electron states are empty as shown in the extreme right of Figure. This is the case of well separated or isolated atoms [region A of Figure].

Suppose these atoms start coming nearer to each other to form a solid. The energies of these electrons in the outermost orbit may change (both increase and decrease) due to the interaction between the electrons of different atoms. The  $6N$  states for  $l = 1$ , which originally had identical energies in the isolated atoms, spread out and form an *energy band* [region B in Figure]. Similarly, the  $2N$  states for  $l = 0$ , having identical energies in the isolated atoms, split into a second band (carefully see the region B of Figure) separated from the first one by an *energy gap*.

At still smaller spacing, however, there comes a region in which the bands merge with each other. The lowest energy state that is a split from the upper atomic level appears to drop below the upper state that has come from the lower atomic level. In this region (region C in Figure), *no energy gap exists where the upper and lower energy states get mixed*.

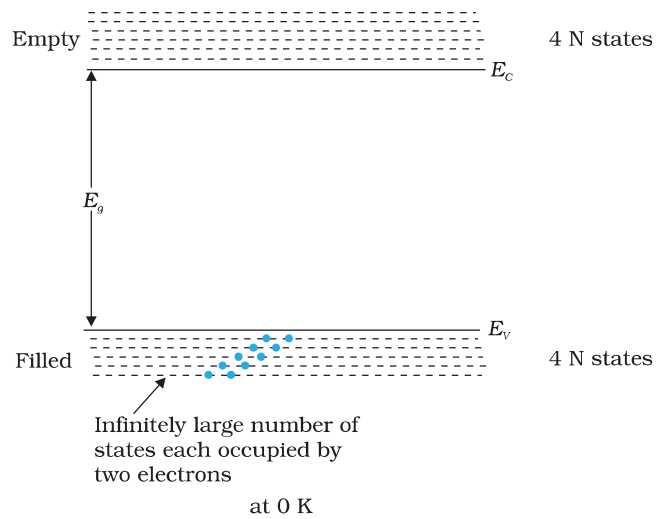
Finally, if the distance between the atoms further decreases, the energy bands again split apart and are separated by an *energy gap*  $E_g$  (region D in Figure). The total number of available energy states  $8N$  has been *re-apportioned* between the two bands ( $4N$  states each in the lower and upper energy bands). Here the significant point is that there are exactly as many states in the lower band ( $4N$ ) as there are available valence electrons from the atoms ( $4N$ ).

Therefore, this band (called the *valence band*) is completely filled while the upper band is completely empty. The upper band is called the *conduction band*.

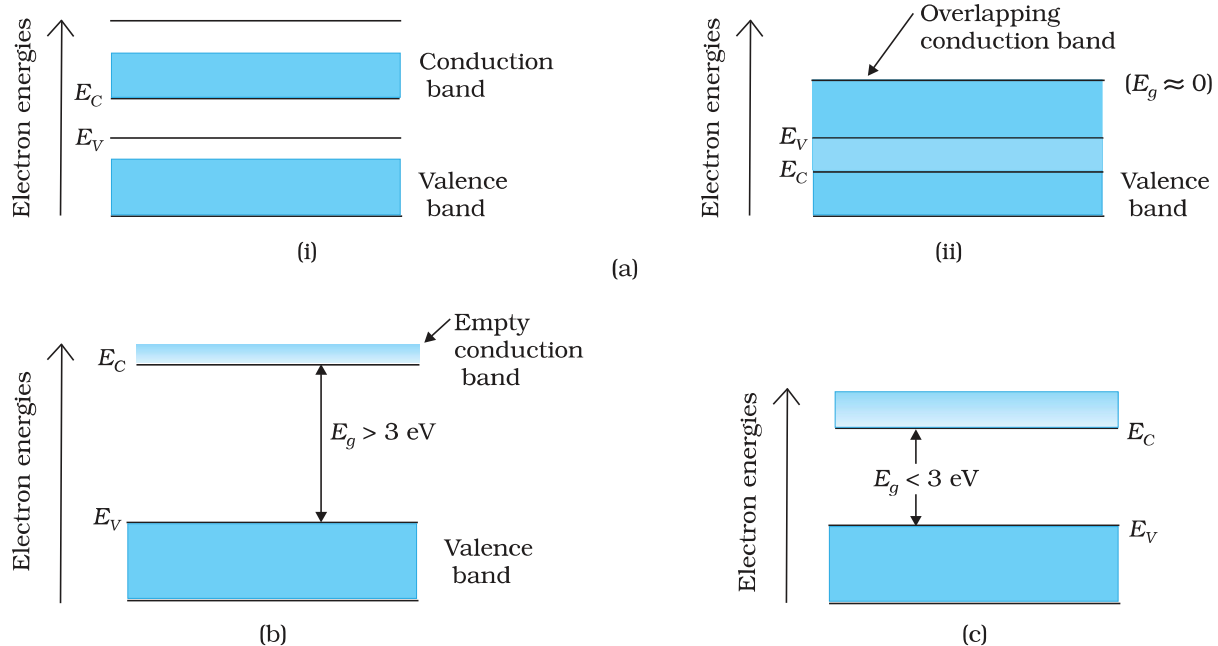
The lowest energy level in the conduction band is shown as  $E_C$  and highest energy level in the valence band is shown as  $E_V$ . Above  $E_C$  and below  $E_V$  there are a large number of closely spaced energy levels, as shown in Fig. 14.1.

The gap between the top of the valence band and bottom of the conduction band is called the *energy band gap* (Energy gap  $E_g$ ). It may be large, small, or zero, depending upon the material. These different situations, are depicted in Fig. 14.2 and discussed below:

**Case I:** This refers to a situation, as shown in Fig. 14.2(a). One can have a metal either when the conduction band is partially filled and the valence band is partially empty or when the conduction and valence bands overlap. When there is overlap electrons from valence band can easily move into the conduction band. This situation makes a large number of electrons available for electrical conduction. When the valence band is partially empty, electrons from its lower level can move to higher level making conduction possible. Therefore, the resistance of such materials is low or the conductivity is high.



**FIGURE 14.1** The energy band positions in a semiconductor at 0 K. The upper band, called the conduction band, consists of infinitely large number of closely spaced energy states. The lower band, called the valence band, consists of closely spaced completely filled energy states.



**FIGURE 14.2** Difference between energy bands of (a) metals, (b) insulators and (c) semiconductors.

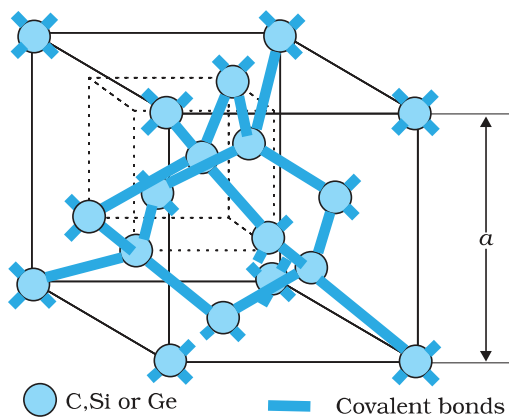
**Case II:** In this case, as shown in Fig. 14.2(b), a large band gap  $E_g$  exists ( $E_g > 3$  eV). There are no electrons in the conduction band, and therefore no electrical conduction is possible. Note that the energy gap is so large that electrons cannot be excited from the valence band to the conduction band by thermal excitation. This is the case of *insulators*.

**Case III:** This situation is shown in Fig. 14.2(c). Here a finite but small band gap ( $E_g < 3$  eV) exists. Because of the small band gap, at room temperature some electrons from valence band can acquire enough energy to cross the energy gap and enter the *conduction band*. These electrons (though small in numbers) can move in the conduction band. Hence, the resistance of *semiconductors* is not as high as that of the insulators.

In this section we have made a broad classification of metals, conductors and semiconductors. In the section which follows you will learn the conduction process in semiconductors.

### 14.3 INTRINSIC SEMICONDUCTOR

We shall take the most common case of Ge and Si whose lattice structure is shown in Fig. 14.3. These structures are called the diamond-like structures. Each atom is surrounded by four nearest neighbours. We know that Si and Ge have four valence electrons. In its crystalline structure, every Si or Ge atom tends to *share* one of its four valence electrons with each of its four nearest neighbour atoms, and also to *take share* of one electron from each such neighbour. These shared electron pairs are referred to as forming a *covalent bond* or simply a *valence bond*. The two shared electrons can be assumed to shuttle back-and-forth between the associated atoms holding them together strongly. Figure 14.4 schematically shows the 2-dimensional representation of Si or Ge structure shown in Fig. 14.3 which overemphasises the covalent bond. It shows an idealised picture in which no bonds are broken (all bonds are intact). Such a situation arises at low temperatures. As the temperature increases, more thermal energy becomes available to these electrons and some of these electrons may break-away (becoming *free* electrons contributing to conduction). The thermal energy effectively ionises only a few atoms in the crystalline lattice and creates a *vacancy* in the bond as shown in Fig. 14.5(a). The neighbourhood, from which the free electron (with charge  $-q$ ) has come out leaves a vacancy with an effective charge  $(+q)$ . This *vacancy* with the effective positive electronic charge is called a *hole*. The hole behaves as an *apparent free particle* with effective positive charge.



**FIGURE 14.3** Three-dimensional diamond-like crystal structure for Carbon, Silicon or Germanium with respective lattice spacing  $a$  equal to 3.56, 5.43 and 5.66 Å.

In intrinsic semiconductors, the number of free electrons,  $n_e$  is equal to the number of holes,  $n_h$ . That is

$$n_e = n_h = n_i \quad (14.1)$$

where  $n_i$  is called intrinsic carrier concentration.

Semiconductors possess the unique property in which, apart from electrons, the holes also move.