4.1 Conductors, Insulators and Semiconductors

4.1.1 Conductors

When a solid is formed the energy levels of the atoms broaden and form bands with forbidden gaps between them. The electrons can have energy values that exist within one of the band and cannot be found in the gaps between the bands. The lower energy bands due to the inner atomic levels are narrower and are full of electrons, so they are not responsible for electronic properties of a material. The outer or valence electrons that bond the crystal together occupy, called valence band.

A band which is full, conducts no current even in the presence of an electric field. In a partial filled band, these exist some free electrons for electric conduction. The tendency of the electrons is always to fill the lower energy band first. The higher energy band that contains electrons (valence band) and the next to this higher band conduction band contribute to the electronic properties of a material [Fig. 4.1(*d*)].

4.1.2 Insulators

In **insulator** the valence band is completely filled and the conduction band is empty. The electrons cannot move since they are fixed in position in chemical bonds. There are no delocalized electrons to carry current, so the material is an insulator. The conduction band is far above the valence band in energy. The energy gap (E_g) between these bands is of the order of 5-10 eV, making it almost impossible for an electrons to cross the gap even if it is thermally or electrically excited as shown in Fig. 4.1 (*a*). Hence these compounds show zero conductivity. Another way to express this is to say that the value of the gap energy E_g far exceeds the value K_BT of the thermal energy, where K_B is Boltzmann's constant. Examples of insulators are diamond (E_g ~ 7eV) NaCl (E_g ~ 6 eV), NaCl (E_g ~ 6 eV).

4.1.3 Semiconductors

In the case of a semiconductor the gap between the valence and conduction bands is much less (Fig. 4.1 (b)) so E_g is closer to the thermal energy $K_B T$ and the heat content of the material at room temperature can bring about the thermal excitation of some electrons form the valence band to the conduction band where they carry current. The forbidden energy gap is of the order of 1 eV or less and the density of electrons reaching the conduction band by this thermal excitation process is relatively low but not negligible. So the electrical conductivity is small. Such type of metals are termed as **semi conductors.** Most of the semiconducting elements belong to group IV of the periodic table, like Si, Ge, Sn etc. There are several semiconducting compounds like GaAs, InSb, GaP, etc, formed by the combination of III and V group elements and ZnS, PbTe, SiC etc. formed by the combination of group II and group VI elements. The band structure of semiconductor shown in Fig. 4.1 (b).

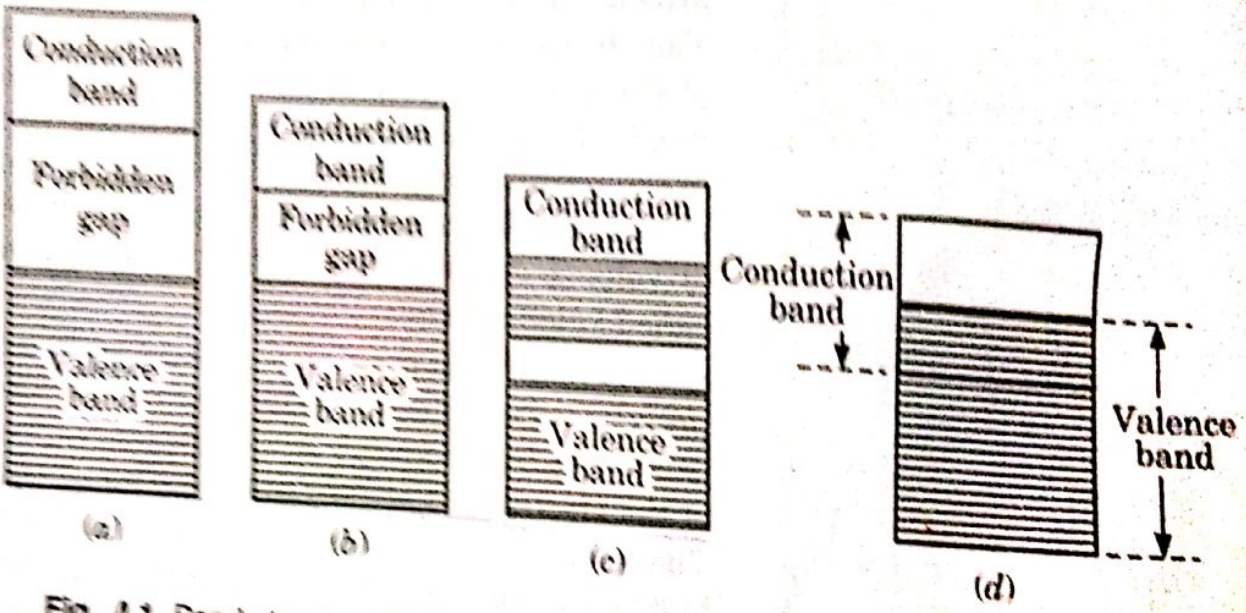

Fig. 4.1. Band structure in (*a*) insulator, (*b*) semiconductor, (*c*) and (*d*) conductor.

4.2 Intrinsic and Extrinsic Semiconductor

Semiconductors can be classified into two types : intrinsic and extrinsic.

4.2.1 Intrinsic semiconductors

They are pure elements like Si and Ge. At 0 K, the valence band is completely filled and the conduction band is empty. The Fermi level (E_F) lies midway between the valence and conduction band edges. As the energy gap is of the order of 1 eV, conduction can be achieved by thermal activation of electrons, when the temperature is raised, electrons near the top of the valence band cross the energy gap to the lower end of the conduction band. This gives rise to a few electrons in the conduction band and leaves an equal number of valencies, called holes, in the valence band. Both the electrons and holes transport charge through the semiconductor and contribute to elect

4.2.2 Extrinsic semiconductors

Semiconductors obtained by adding impurities known as doping to pure semiconductors are called extrinsic semiconductors. Depending on the type of impurity used, semiconductors can be classified into *n* type and *p* type Fig. 4.3 (*a*, *b*).

If a group V (pentavalent) element like arsenic or phosphor is added to the group IV element, four electrons of the group V element combine with those of the group IV element to form covalent bonds. The remaining one electron of the impurity atom is very weakly bonded with the parent atom and can easily be excited to the conduction band. This type of material in which, the conduction is due to these free electron (charge carrier) is called an *n* type Semiconductor.

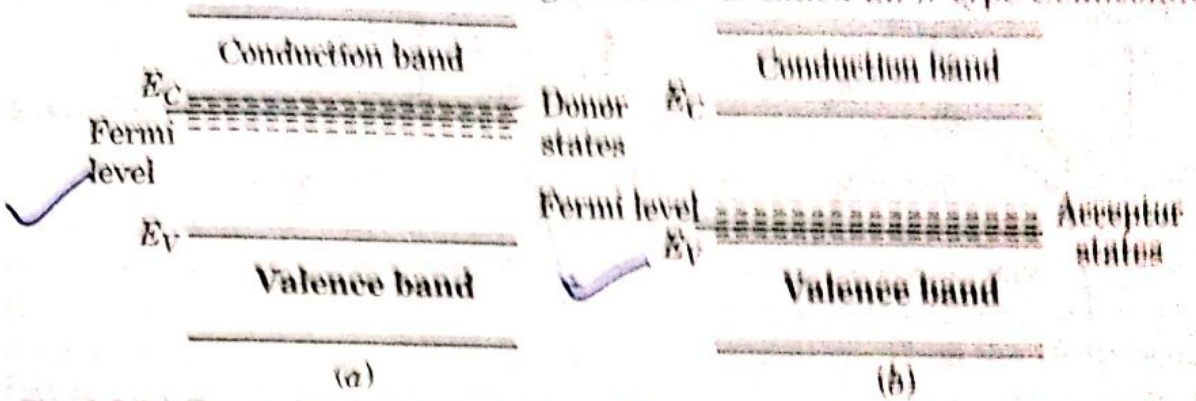

Fig. 4.2 (*a*) Energy levels of donor atoms. The donor levels are about 0.01 eV (Ge) and 0.05 eV (Si) below the conduction band edge. (*b*) Energy levels of acceptor atoms. The acceptor levels are about 0.01 eV (Ge) and 0.05 (Si) above the valence band edge.

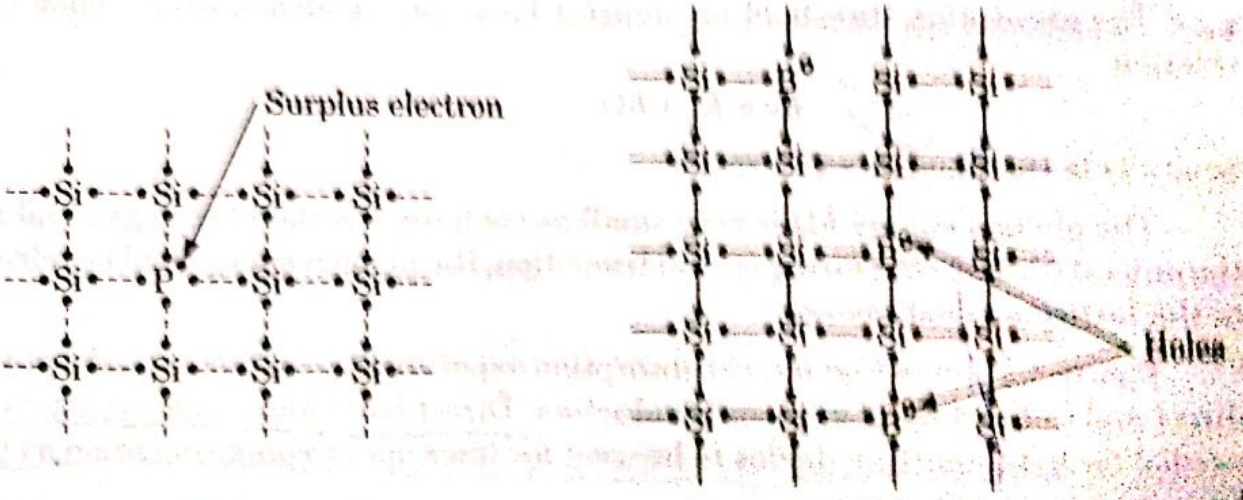

Fig. 4.3. (*a*) (*b*)

The impurity atom which donates free electrons to the crystal is called the donor. The donor energy levels lie below the conduction band edge [Fig. 4.2 (*a*)]. In *p*-type semiconductors the fermi level is closer to the valence band edge.

If the doping is by group III elements, all the three valence electrons enter into covalent bonding, leaving the valency of an electron to form saturated bonds. Thus, the doping creates a hole. The material is called a *p*-type semiconductor with holes as the majority charge carriers. The impurity is called an acceptor impurity. Acceptor levels lie just above the valence band edge [Fig. 4.2 (*b*)]. Fermi level shifts upward and lies close to the conduction band in *n*-type semiconductors.

.3 Direct and Indirect Band Gap Semiconductors

In direct band gap semiconductor the top edge of the valence band and the bottom edge of the conduction band occur for the same point. Only a photon is involved between the transitions. In indirect band gap semiconductors, both a photon as well as a phonon is involved in the transitions as the band edges of the valence and conduction bands are separated by a finite k vector. (Fig. 4.4)

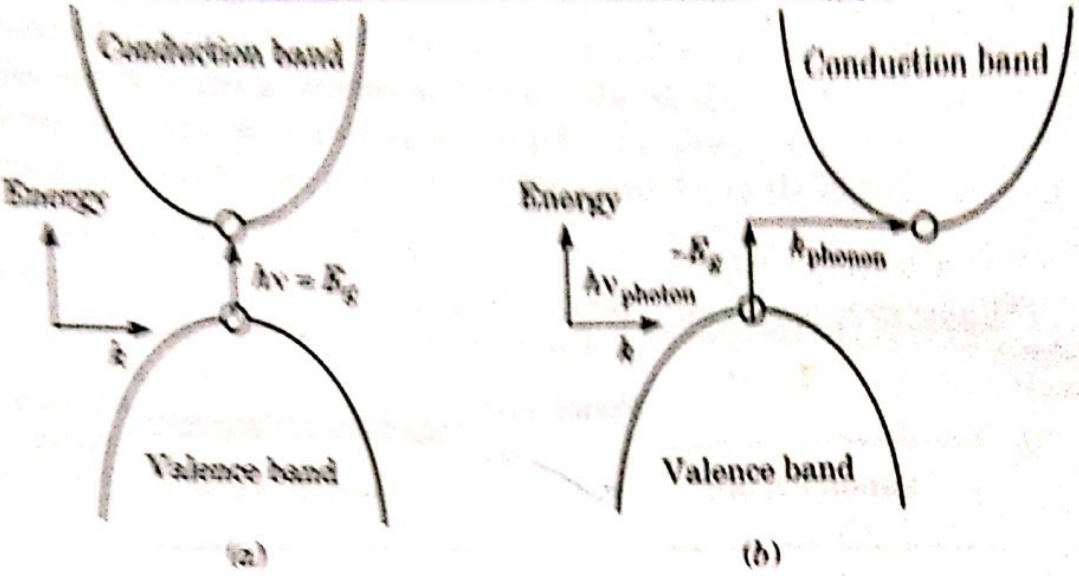

Fig. 4.4. Band structure of: (a) direct and (b) indirect band gap semiconductors. The conduction band minimum and the valence band maximum need not occur at the symmetry point Γ in all intrinsic semiconductors.

The absorption threshold for indirect band gap semiconductors follows the relation

$$h\nu = E_g + \hbar\Omega$$

where Ω is the phonon wave vector.

The phonon energy $\hbar\Omega$ is very small as compared to the energy gap and is of the order 0.01-0.03 eV. During optical transition, the phonon energy will be released to the lattice as heat energy.

Figure 4.5 shows that optical absorption experiments can distinguish between direct and indirect band gap semiconductors. Direct band gap semiconductors are needed for light emitting diodes to be used for fiber optics communication as they have maximum efficiency.

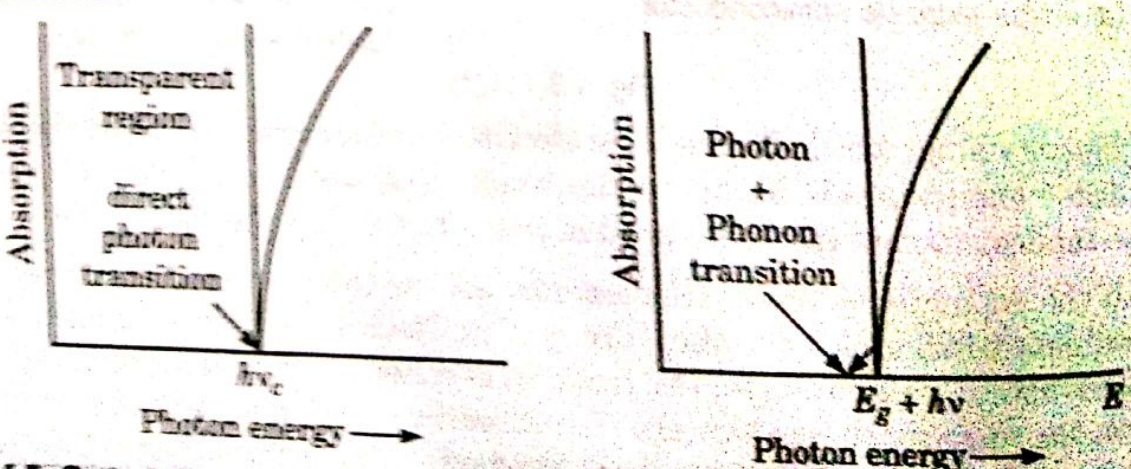

Fig. 4.5. Optical absorption spectra for (a) direct and (b) indirect band gap semiconductors