

6

physics of Semiconductors

6.1 FORMATION OF ENERGY BANDS IN SOLIDS

The energy of electrons in an atom cannot have any arbitrary value but only some definite values in accordance with quantum mechanical laws. In a free atom, the energy levels are well-defined. However, for an atom in a solid, where it is surrounded by other atoms, the energy levels get modified. This modification is not significant in the energy levels of the electrons in the inner shells. But the energy levels of the electrons in the outer shells, particularly in the outermost shell, get appreciably modified. This is because the electrons in the outermost shells are shared by more than one atom in the solid.

In order to understand the modification of energy levels, we consider silicon crystal having N atoms. The electronic configuration of a silicon atom is $1s^2 2s^2 2p^6 3s^2 3p^2$. The outer shell contains 2 electrons in $3s$ subshell and 2 electrons in $3p$ subshell. In the outermost shell $2N - 3s^2$ energy levels are completely filled while $6N - 3p^6$ energy levels are only partially occupied by $2N$ electrons, i.e., only $2N$ energy levels are filled.

Figure 6.1 shows the energy levels of silicon atom in the crystal. The actual interatomic separation is d_0 , i.e., $r = d_0$. To understand that how energy levels get modified, let us imagine the atoms are brought near to each other to form the crystal such that finally the interatomic separation reduces to d_0 . We discuss energy levels at four interatomic separations.

(i) At $r = d_3$. (At this interatomic separation, electrons in one atom do not get influenced by the other atoms. Therefore, each N atom retains its energy levels unperturbed.)

(ii) At $r = d_2$. (On reducing the interatomic separation to d_2 , the interaction between the electrons in the outermost shell becomes appreciable. As a result, $3s$ and $3p$ energy levels of the atoms get slightly changed and instead of isolated energy levels, closely packed energy levels result. Now, the $2 N s$ -levels will not have same energy but will be spread in small energy band. Similarly, $6 N p$ -levels will also spread into a small energy band. This spreading of energy reduces the energy gap between $3p$ and $3s$ levels compared to that in an isolated atom.) Because there are approximately 10^{29} atom/m³ the energy levels due to spreading of $3s$ and $3p$ levels are very closely spaced. *The collection of closely spaced energy levels is referred to as energy band.* In each band, energy levels are very closely spaced, the spacing

between successive levels is of order of $\left(\frac{\hbar^2}{mV^{2/3}}\right)$, where $\hbar \left(\hbar = \frac{h}{2\pi} \right)$ is Planck's constant, m the electronic mass and V the volume of the solid.

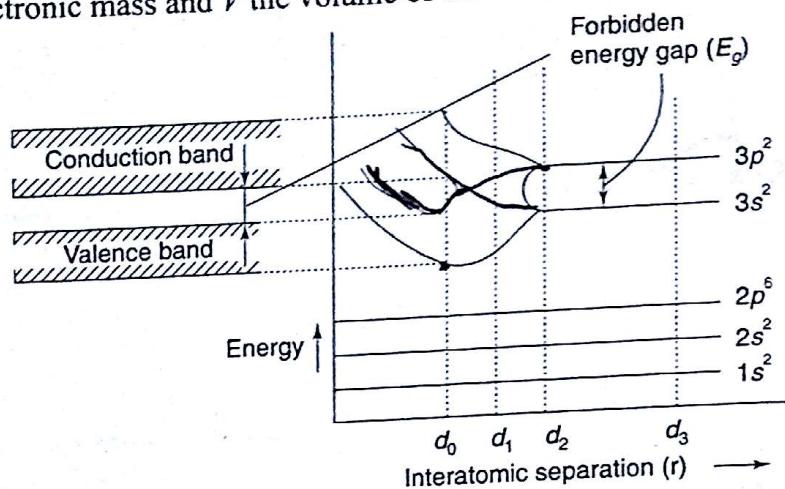


Fig. 6.1

(ii) At $r = d_1$. On further reduction of interatomic separation to d_1 , the energy gap between $3s$ and $3p$ levels completely disappears and the $8N$ levels ($2N$ s -level and $6N$ p -level) are continuously distributed forming an energy band. In such a situation, it is not possible to distinguish between the electrons belonging to $3s$ and $3p$ subshells. It can only be said that $4N$ levels are filled and $4N$ levels are empty.

(iv) At $r = d_0$. When the interatomic separation reduces to the equilibrium distance in the actual crystal ($r = d_0 \approx 1 \text{ \AA}$), the band of $4N$ filled energy levels and the band of $4N$ empty levels get separated by an energy gap called the forbidden energy gap, E_g . The lower completely filled band is called the *valence band* and the upper empty energy band is called the *conduction band*.

Depending on the magnitude of the forbidden energy gap E_g , solids are classified as metals, semiconductors and insulators. We discuss below this classification in detail.

6.2 DISTINCTION BETWEEN METALS, INSULATORS AND SEMICONDUCTORS

Metals are good conductors of electricity, insulators are very poor conductors of electricity, and the conductivity of semiconductors lies in between that of metals and insulators.

Fermi level is a hypothetical level in the energy levels of a crystal (corresponding energy is Fermi energy) all energy levels below which are completely occupied at zero Kelvin and levels above it completely empty. As the temperature is raised above zero Kelvin, some of the electrons acquire enough thermal energy to cross over the Fermi level and jump to conduction band. The electrons in conduction band are free to move inside the crystal and the movement of these free electrons constitute the electric current. The magnitude of the forbidden energy gap determines the number of free electrons available in the conduction band and hence conductivity of a solid at a particular temperature. From the electrical conductivity point of view solids are generally classified as metals, semiconductors and insulators, discussed below (we do not include superconductors as they are special class of materials and also at present superconductors are not available at room temperature).

(i) **Metals:** The energy band structure of a metal is shown in Fig. 6.2. There are two possible arrangements of energy bands which leads to metallic behaviour of a crystal. In the first kind, an empty conduction band overlaps the completely filled valence band [Fig. 6.2(a)]. Such a metal is called a *band overlap metal*. The second possibility is that *conduction band is partially filled* [Fig. 6.2 (b)]. Zinc and sodium are a typical example of the first and second kind of metals, respectively.

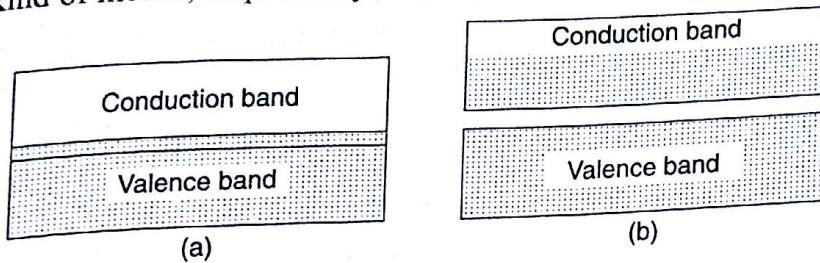


Fig. 6.2

Now, let us try to understand why these metals conduct electricity. Suppose, an electric field E is applied to the metal. Each electron in the metal experiences a force eE , gets accelerated and starts moving towards the positive electrode, i.e., in a direction opposite to that of the applied field. If l is the mean free path, then each electron gains energy equal to eEl , which works out to be of the order of the 10^{-8} eV for a typical applied field. Thus, if unoccupied states within 10^{-8} eV are available, the electrons jump into them which is the case in the metals as unoccupied states are close, i.e., within 10^{-8} eV. In such a case, the process of conduction, namely acceleration, collision and return to equilibrium, leading to steady drift of electrons, can occur. That is how, the metals conduct electricity.

(ii) **Insulators:** The energy band structure of an insulator is shown in Fig. 6.3. The magnitude of forbidden energy gap E_g is quite large, generally 6 to 9 eV. For diamond, an insulator, it is 6 eV. This means that an electron requires a minimum of 6 eV of energy to jump from valence band to conduction band. When an electric field is applied, the electrons do not acquire sufficient energy to do so and the conduction band continues to be almost empty. So conduction is not possible and therefore insulators are very poor conductors of electricity. However, at any non-zero temperature, a few electrons (a fraction $p \propto e^{-E_g/kT}$ according to Boltzmann law) acquire sufficient energy to jump to the conduction band and therefore the conduction band is not fully empty and a small conductivity (proportional to p) results.

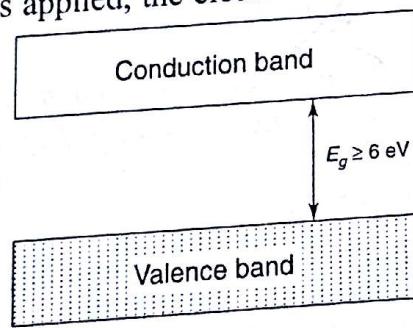


Fig. 6.3

(iii) **Semiconductors:** The energy band structure of a semiconductor is shown in Fig. 6.4. It is similar to that of an insulator but with a smaller magnitude of forbidden energy gap, nearly 1 eV. At absolute zero temperature (0 K) the Fermi levels lie in the middle of forbidden energy gap and therefore the valence band is completely filled and the conduction band is totally empty. The absence of electrons in the conduction band at absolute zero will not allow current to flow under the influence of an applied

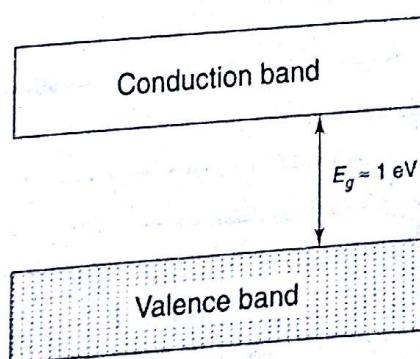


Fig. 6.4

electric field. Therefore, at absolute zero there is no difference between an insulator and a semiconductor from electrical conductivity point of view.

However, at room temperature some valence electrons acquire enough thermal energy (greater than E_g) to cross over to the conduction band and they are free to move under the influence of applied electric field. This fraction is $p \propto e^{-E_g/kT}$. Since E_g is smaller in case of semiconductors (≈ 1 eV) than that in insulators (≈ 6 eV), this fraction is sizeable for semiconductors. Thus, the crystal becomes slightly conducting at room temperature and that is why such crystals are known as semiconductors.

The forbidden energy gap is weakly dependent on temperature.

It has been found that for

$$Si : E_g(T) = 1.21 - 3.60 \times 10^{-4} T; \text{ at } T = 300 \text{ K}, E_g = 1.1 \text{ eV}$$

$$Ge : E_g(T) = 0.785 - 2.23 \times 10^{-4} T; \text{ at } T = 300 \text{ K}, E_g = 0.72 \text{ eV}$$

Thus, it decreases slightly with increasing temperature.

Higher the temperature, larger is the number of electrons jumping to the conduction band and hence greater is the conductivity. Each electron moving to the conduction band leaves behind a vacancy called a hole in the valence band, which behaves as a short of positive charge carrier.

The distinction between insulators and semiconductors is quantitative, not qualitative. In both types of solids, the valence band and the conduction band is separated by forbidden energy gap. If the forbidden energy gap $E_g \approx 1$ eV or so, the solid is categorized as semiconductor while if $E_g > 5$ eV, we say that the solid is an insulator. The carrier density (charge carriers per unit volume) and hence the conductivity depends exponentially on the ratio of the energy gap E_g to the temperature of the crystal. This ratio varies from nearly 30 for a semiconductor to about 150 for an insulator change. The typical room temperature resistivities for metals, semiconductors and insulators are $10^{-8} \Omega\text{m}$, $10^2 \Omega\text{m}$ and $10^{10} \Omega\text{m}$ respectively.

~~Example 6.1~~

The mean free path of conduction electrons in copper is about 4×10^{-8} m. In this conductor, what electrical field should be applied so that a conduction electron acquires 1.2 eV average energy?

Solution.

Let the electric field required be E . The force on an electron is eE . When an electron moves through a distance l in the field, the work done on it is eEl , which is also the energy acquired by it. An electron travels, on an average, a distance 4×10^{-8} m before collision. Therefore, average energy is $eE \times (4 \times 10^{-8}$ m). Thus,

$$eE \times (4 \times 10^{-8} \text{ m}) = 1.2 \text{ eV}$$

or

$$eE \times (4 \times 10^{-8} \text{ m}) = 1.2 \times 1.6 \times 10^{-19} \text{ J}$$

or

$$E = \frac{1.2 \times 1.6 \times 10^{-19}}{e \times 4 \times 10^{-8}} \frac{\text{V}}{\text{m}} = \frac{1.2 \times 1.6 \times 10^{-19}}{1.6 \times 10^{-19} \times 4 \times 10^{-8}} \frac{\text{V}}{\text{m}}$$

or

$$E = 3.0 \times 10^7 \text{ V/m.}$$

6.3 CURRENT CARRIERS (ELECTRONS AND HOLES) IN SEMICONDUCTORS

Figure 6.5 shows the energy band diagram of a pure semiconductor. Figure 6.5(a) shows a few electrons in the valence band at absolute zero of temperature, while Fig. 6.5(b) depicts the situation at a higher (say room) temperature. As we have discussed earlier, at higher temperatures, some of the electrons in the valence band acquire sufficient thermal energy to cross over to the conduction band. For each electron that leaves the valence band a vacancy is created at the location where the electron was present before moving to the conduction band [Fig. 6.5(b)]. This vacancy is called a hole.

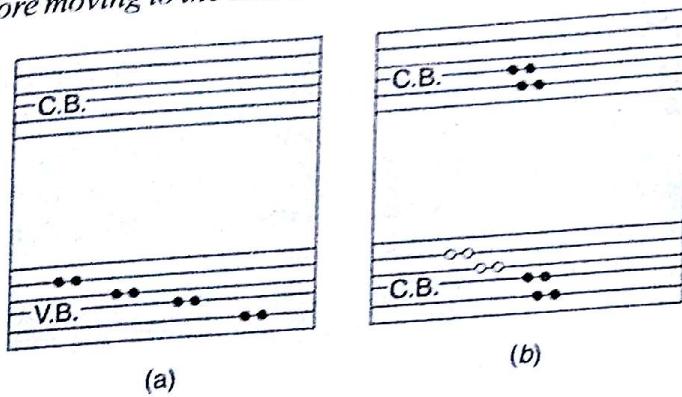


Fig. 6.5

The mechanism of hole creation can also be understood with the help of Fig. 6.6. In the figure the crystal structure of germanium, a semiconductor, is shown. The atoms in the structure are strongly held by covalent bonds. On receiving an addition energy, one of the electrons contributing to a covalent bond breaks and is free to move in the crystal. While coming out of a covalent bond, it leaves behind a hole.

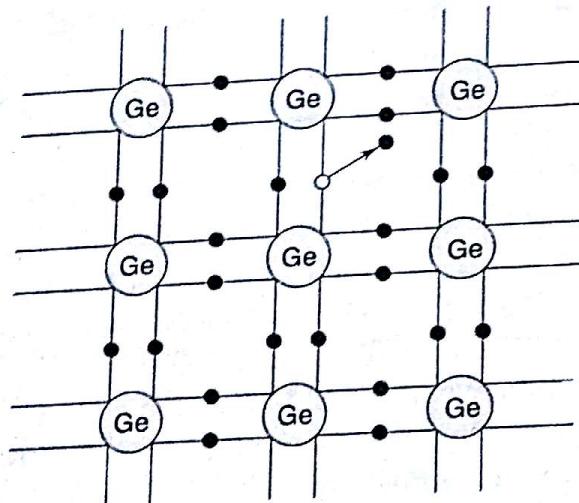


Fig. 6.6 Breaking of a covalent bond in a Ge crystal.

An electron from the neighbouring atom can break away and occupy the existing vacancy (or hole) completing the covalent bond and creating a hole at another site. In our two-dimensional example shown in Fig. 6.6, an electron from any of the neighbouring atom can come to complete the bond and the hole can move to any of these atoms. In this manner, holes move randomly in the crystal lattice. In real situations, free electrons may also fill up the vacancy. This is also known as *electron-hole recombination*.

In a crystal, the breaking of bonds or generation of electron-hole pairs and completion of bonds due to recombination occur all the time. In equilibrium, the rate of (electron-hole pair) generation equals that of recombination, maintaining a fixed number of electrons and holes.

Movement of holes under the influence of an applied electric field. Now we will try to understand that how the holes move under the influence of an applied electric field with the help of an over simplified diagram shown in Fig. 6.7. In the figure five atoms at four instants of time have been shown in a semiconductor crystal. Suppose, initially there are no free electrons and all the electrons are bound in the covalent bonds. Further suppose, that thermal excitation breaks a covalent bond at atom-1 setting an electron free and creating a hole, i.e., generates an electron-hole pair. The electron generated moves to positive terminal of the battery while the hole remains at atom-1. Due to the applied field, an electron from atom-2 goes atom-1 and fill the vacancy in atom-1 but in the process creates hole at atom-2. Similarly, an electron from atom-3 moves at atom-2 and the hole moves to atom-3. Continuing in this way, the hole moves to atom-5 which takes an electron from the negative terminal of the battery and the covalent bond is completed. Thus, the electron initially lost to the positive terminal of the battery has been finally compensated by the negative terminal of the battery and this manner an electron has travelled from negative to the positive terminal of the battery through the crystal, constituting a current in the crystal.

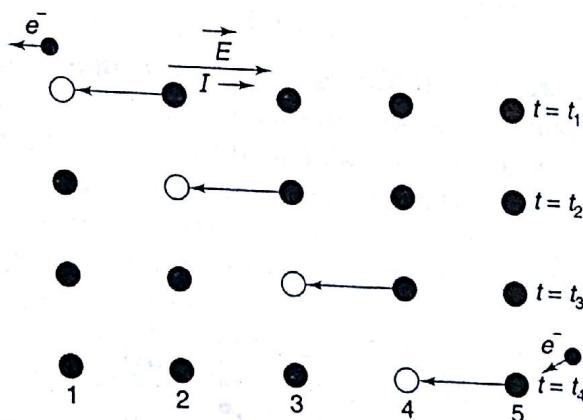


Fig. 6.7 Movement of a hole under an electric field at different instants of time in a semiconductor.

From the above discussions, we notice that holes move in a direction opposite to that of electrons, i.e., they behave as *positively charged* particles. A hole is a convenient way of describing charge motion in semiconductors, although motion can be described entirely in terms of electrons.

In a semiconductor, when both electrons and holes are present, and are, far away from each other, they carry current independently. If I_e is the component of current carried by electrons and I_h that by holes, then the total current I is given by

$$I = I_e + I_h \quad \dots(6.1)$$

Sometimes I_n for I_e for I_p and I_h are also used, in such notations the total current is $I = I_n + I_p$.

To create a hole an electron has to be removed. To remove an electron from the inner orbit, larger amount of energy is required. Thus, we can say that the hole farther from the top of the valence band has higher energy, just as an electron in the conduction band, farther away from its bottom has higher energy.

6.4 INTRINSIC SEMICONDUCTORS

Pure semiconductors are called *intrinsic semiconductors*. In intrinsic semiconductors, thermally generated electron-hole pairs exists and in the absence of any applied electric field, these electrons and holes move randomly. These electrons and holes are called *intrinsic carriers*. Because electrons and holes are holes are created in pairs, i.e., a hole is created when an electron becomes free, in an intrinsic semiconductors

$$n = p = n_i$$

Where n is the electron density in conduction band, p is the hole density in the valence band and n_i is the intrinsic concentration.

In Table 6.1, energy gap (E_g), mobility (μ), intrinsic carrier concentration (n_i), conductivity (σ), resistivity, density and concentration of atom of pure Si and Ge, two widely used semiconductors, are given.

Table 6.1

	Si	Ge
Energy gap E_g (eV)	1.1	0.7
Intrinsic conductivity σ (Sm^{-1})	4.4×10^{-4}	2.18
Intrinsic resistivity ρ ($\Omega \text{ m}$)	2300	0.46
Intrinsic carrier concentration n_i (m^{-3})	1.5×10^{16}	2.4×10^{19}
Density (kgm^{-3})	2.3×10^9	5.32×10^9
Concentration of atom (m^{-3})	5×10^{28}	4.41×10^{28}
Electron mobility μ_n ($\text{m}^2 \text{ V}^{-1} \text{ s}^{-1}$)	0.135	0.39
Hole mobility μ_p ($\text{m}^2 \text{ V}^{-1} \text{ s}^{-1}$)	0.048	0.19

6.5 DOPING OF SEMICONDUCTORS: EXTRINSIC SEMICONDUCTORS

The intrinsic semiconductors, at room temperature possess thermally generated free electrons and holes but their number is too small and so that the conductivity is too small to be of any practical use. To increase their conductivity suitable impurities are added in pure semiconductors. This deliberate addition of a desirable impurity is called 'doping' and the impure atoms added are called 'dopants'. A doped semiconductor is called an extrinsic semiconductor.

The dopant atoms should be such that they preferably substitute semiconductor atoms and should not distort the crystal lattice which is possible if the dopant atoms are of same size as that of the pure semiconductor crystal atoms. The concentration of dopant atoms are generally kept below 1% of the semiconductor crystal atoms. Doping is done in a number of ways.

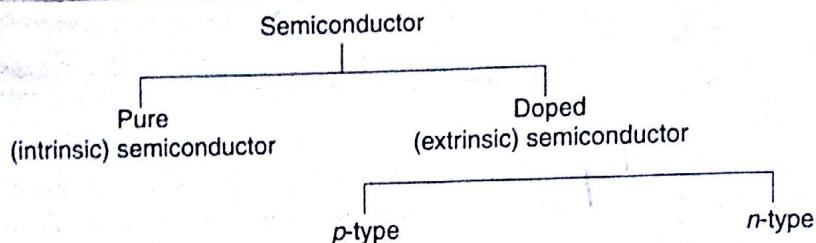
Three commonly employed methods are mentioned below:

- (i) One way is to add the impurity atoms in the melt of the semiconductor.
- (ii) Another way is to heat the crystalline semiconductor in the atmosphere containing dopant atoms or molecules, i.e., to diffuse dopant atoms into the crystalline semiconductor.
- (iii) The semiconductor to be doped is bombarded by the ions of the dopant atoms.

TYPES OF EXTRINSIC SEMICONDUCTORS: N- AND P-TYPE SEMICONDUCTORS

The most commonly used semiconductor materials used for manufacturing semiconductor materials for devices are tetravalent elements such as silicon (Si) and germanium (Ge). However, for specialized

application GaAs, SiC, etc. are becoming very useful. To increase the conductivity the pure semiconductors are doped by suitable impurities. Depending upon the kind of impurities added, there are two types of extrinsic semiconductor or : *n*-type and *p*-type.



P AS

N-Type (Extrinsic) Semiconductor. If we dope intrinsic semiconductor, say silicon, which has four valence electrons, with a controlled amount of pentavalent atoms like arsenic As (or antimony Sb or phosphorus P), which have five valence electrons, the added atoms substitute the silicon atoms [Fig. 6.8(a)]. Out of the five valence electrons of an arsenic atom, four electrons enter in covalent bonds with the four silicon atoms surrounding it, while the fifth electron not being part of any bond, is comparatively free. Obviously, the number of free electrons will be equal to the number of atoms added. Thus, each pentavalent atom added releases one free electron to the host crystal and it is for this reason that the pentavalent atoms are called the donor atoms. Because of these free electrons in the doped crystal, the doped crystal is called *n*-type Si crystal. The electrons set free are called extrinsic carriers and the semiconductor is called *n*-type extrinsic semiconductor. On giving up the fifth electron the donor atom acquires positive charge although the crystal as a whole remains electrically neutral.

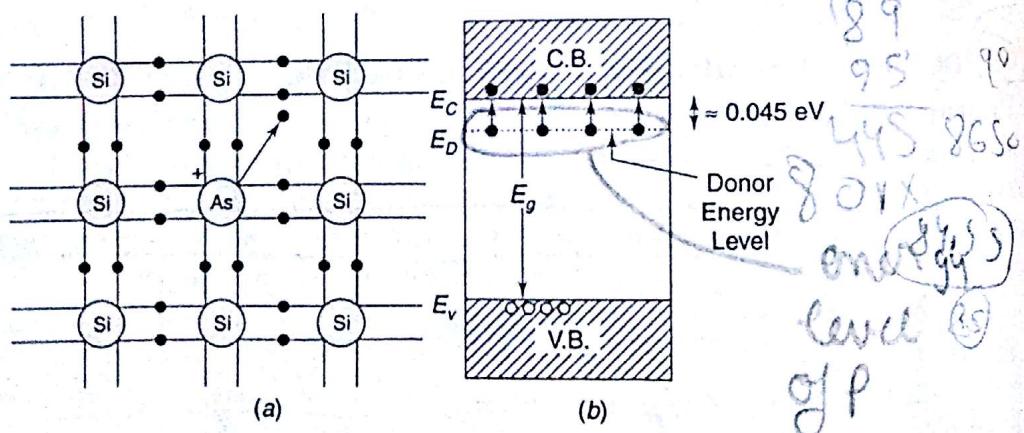


Fig. 6.8 *N*-type semiconductor.

Like pure semiconductors, thermally generated electron-hole pairs exist in doped semiconductors also. But due to excess (free) electrons in the *n*-type extrinsic semiconductors, the number of free electrons is much higher than that of holes. For this reason, in *n*-type semiconductors, electrons are called majority carriers and holes are called minority carriers.

The fifth electron of the donor atom, not a part of any covalent bond, is very loosely bound to the nucleus. This we can realize from the following discussion. The electron moves in crystalline silicon (or germanium) which has a relative dielectric constant of nearly ten. This means the coulomb attraction between the electron and the nucleus is ten times smaller than what it would have been in

free space. The binding energy of this electron works out to be only 0.45 eV. Thus, to free the fifth electron from the donor atom only 0.045 eV of energy is needed. In terms of band structure, it is equivalent to say that such electrons (extrinsic carriers) create a donor energy level just below (0.045 eV) the conduction bond, as shown in Fig. 6.8(b). This energy (0.045 eV) is comparable to room temperature thermal energy $kT \approx 0.03$ eV, and is much smaller than the energy gap of 1.1 eV. Since it requires only 0.045 eV of energy by these electrons to go to the conduction band, at room temperature, a large fraction of donor electrons is in the conduction band giving a good conductivity. Even for low donor concentration the number of extrinsic carriers are much larger than that of intrinsic carriers at non-zero temperatures. At room temperature, most of the donor atoms are ionized, so that to a good approximation we can assume that the fifth electron from all the donor atoms are in the conduction band.

(In a doped semiconductor, the number densities of conduction band electrons n and the valence band holes p differ from that in a pure semiconductor. If n_i is the number density of intrinsic carriers, then we have the relation.

$$np = n_i^2 \quad \dots(6.3)$$

In *n*-type semiconductors, the number density of electrons in conduction band is much larger than that of holes in valence band and is nearly equal the density of donor atoms (N_D) in the doped semiconductor, that is

$$n_e = N_D \gg p \quad \dots(6.4)$$

In other words, electrons are majority carriers and holes are minority carriers.

P-Type (Extrinsic) Semiconductor If we dope an intrinsic semiconductor, say silicon, with a controlled amount of trivalent atoms, say indium (In) (or boron B or aluminium Al) which have three valence electrons, the added atoms substitute some Si atoms [Fig. 6.9(a)]. Because the dopant atom has only three valence electrons, there is one incomplete bond with a neighbouring Si atom, due to deficiency of an electron. The bond is completed by taking an electron from one of the neighbouring Si-Si bonds. In the process an atom acquires negative charge and a hole is created in the crystal, as shown in Fig. 6.9(b). As the trivalent dopant atoms accept electrons from the silicon crystal, they are also called acceptor atoms. The semiconductor obtained by adding acceptor atoms is called *p*-type (extrinsic) semiconductor as it contains excess holes. Each hole is equivalent to a positive charge.

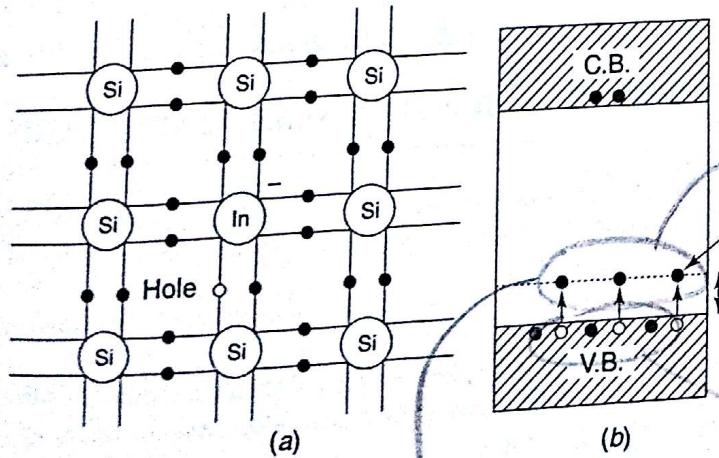


Fig. 6.9 *p*-type semiconductor.

energy level
of B

e with Si
holes made
responsible
for conduction

In *p*-type semiconductors besides, thermally generated holes (due to creation of electron-hole pairs) dopant atoms create one hole per added atom. Therefore, number of holes is much larger than free electrons and that is why *holes are majority carriers and electrons are minority carriers*.

The hole produced is attracted to the negatively charged acceptor nucleus. Such holes create an acceptor energy level just above (≈ 0.04 eV) the top of the valence band [Fig. 6.9(b)]. This means that electrons in the valence band require only nearly 0.04 eV of energy to raise themselves to acceptor energy level, which is comparable to the room temperature thermal energy, and thus create holes in the valence band.

Number density of holes p in the valence band in a *p*-type semiconductor is approximately equal to the number density of added acceptor atoms N_A and is very large compared to the number density of electrons n . That is,

$$p \approx N_A \gg n_e \quad \dots(6.5)$$

6.7 COMPARISON BETWEEN INTRINSIC AND EXTRINSIC SEMICONDUCTOR

<i>Intrinsic (Pure) Semiconductor</i>	<i>Extrinsic (Doped) Semiconductor</i>
<ol style="list-style-type: none"> 1. Intrinsic semiconductor does not contain any added impurities. 2. Its electrical conductivity is very low. 3. There is no classification of intrinsic semiconductors. 4. The number of free electrons in conduction band is always equal to the number of holes in valence band. 5. Rarely used in semiconductor devices. 6. Its electrical conductivity is a function of temperature only. 7. Examples are pure Si and Ge crystals. 	<p>Extrinsic semiconductor contains suitable impurities added to it.</p> <p>Its electrical conductivity is high.</p> <p>Extrinsic semiconductors are of two types: <i>n</i>-type and <i>p</i>-type.</p> <p>In <i>n</i>-type semiconductors, the number of electrons in conduction band is larger than that of holes in valence band while reverse is true in a <i>p</i>-type semiconductor.</p> <p>Widely used in semiconductor devices.</p> <p>Its electrical conductivity is dependent on the amount of doping as well as temperature.</p> <p>Examples are arsenic (or phosphorus or antimony) doped Si (or Ge) crystal for <i>n</i>-type and indium (or Al or boron) doped Si (or Ge) crystal for <i>p</i>-type.</p>

6.8 COMPARISON BETWEEN N- AND P-TYPE SEMICONDUCTORS

<i>N-Type Semiconductor</i>	<i>P-Type Semiconductor</i>
<ol style="list-style-type: none"> 1. N-type semiconductor is obtained by doping intrinsic semiconductor by pentavalent impurities such as arsenic or antimony or phosphorus. 2. Electrons are majority carriers and holes are minority carriers. 3. The added impurity atoms are called donor atoms as they donate one excess electron per added atom. 	<p>P-type semiconductor is obtained by doping intrinsic semiconductor by trivalent impurities such as indium, aluminum or boron.</p> <p>Holes are majority carriers and electrons are minority carriers.</p> <p>The added impurity atoms are called acceptor atoms as they accept one electron per added atom.</p>

Contd...

4. Donor energy level is just below the conduction band.
5. Due to higher mobility of electrons, for the same level of dopings as in a p-type semiconductor, it has higher electrical conductivity.
- Acceptor energy level is just above the valence band.
Due to comparatively lower mobility of holes for the same level of doping as in a n-type semiconductor, it has lower electrical conductivity.

6.9 CHARACTERISTICS OF A SEMICONDUCTOR

The important characteristics of semiconductors are listed below.

1. At absolute zero and very low temperature a pure semiconductor behaves as an insulator. As temperature is increased few electrons in the valence band acquire energy greater than forbidden gap energy and move to conduction band. At room temperature it becomes slightly conducting.

2. The conductivity of semiconductors increases with increasing temperature. This is in contrast with the behaviour of metals in which conductivity decreases with increasing temperature.

3. There are two types of carriers in semiconductors, namely electrons and holes.

4. Very small amount of doping (≈ 1 impurity atom in 10^6 atoms) improves the conductivity drastically.

5. Doped semiconductors do not obey Ohm's law.

In semiconductors electrons have higher mobility than that of holes.

6.10 ELECTRICAL CONDUCTIVITY OF EXTRINSIC SEMICONDUCTORS

Consider a slab of an extrinsic semiconductor having length l and area of cross-section A .

Let n be the electron density (number of electrons per unit volume) and p that of holes. When a potential difference V is applied across it, a current I flows through it, as shown in Fig. 6.10. In a semiconductor the total current I consists of two components, the electronic current I_e due to motion of electrons (in conduction band) directed towards positive terminal and current I_p due to motion of holes (in valence band) directed towards negative terminal. Thus,

$$I = I_e + I_p \quad \dots(6.6)$$

We know the current I in a conductor having area of cross-section A is given by

$$I = enA v_d$$

where n is the number density of charge carrier, e is the charge on a carrier and v_d , the drift velocity of the carriers. For the electronic current, we have

$$I_e = enA v_e \quad \dots(6.7)$$

where n is the number density of electrons, e the electronic charge and v_e is drift velocity of electrons.

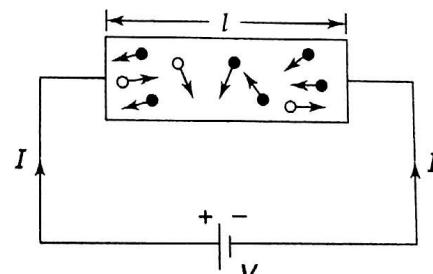


Fig. 6.10

$$I_p = e p A v_h \quad \dots(6.8)$$

where p is number density and v_h drift velocity of holes. The charge e on a hole is equal in magnitude to that on an electron but opposite, i.e., positive in sign.

From Eqs. (6.6), (6.7) and (6.8), we have

$$\begin{aligned} I &= en A v_e + ep A v_h \\ \text{or } I &= e A(n v_e + p v_h) \end{aligned} \quad \dots(6.9)$$

Using the relation $V = IR$ or $I = \frac{V}{R}$, we have

$$\frac{V}{R} = e A (n v_e + p v_h) \quad \dots(6.10)$$

Also, $R = \rho \frac{l}{A}$

$$\dots(6.11)$$

where ρ is the resistivity of the semiconductor.

From Eqs. (6.10) and (6.11), we get

$$\frac{VA}{\rho l} = e A (n v_e + p v_h)$$

or $\frac{V}{\rho l} = e (n v_e + p v_h)$

But $\frac{V}{l} = E$ is the electric field set up across the semiconductor.

$$\therefore \frac{E}{\rho} = e (n v_e + p v_h) \quad \dots(6.12)$$

Dividing the above equation by E , we have

$$\frac{1}{\rho} = \frac{e}{E} (n v_e + p v_h)$$

or $\frac{1}{\rho} = e \left(n \frac{v_e}{E} + p \frac{v_h}{E} \right)$

The quantities $\frac{v_e}{E} = \mu_e$ and $\frac{v_h}{E} = \mu_h$ denote mobility of electrons and holes respectively. Thus,

$$\frac{1}{\rho} = e (n \mu_e + p \mu_h)$$

or, conductivity $\sigma \left(= \frac{1}{\rho} \right) = e (n \mu_e + p \mu_h) \quad \dots(6.13)$

From Eq. (6.13) it is clear that *conductivity is proportional to electron and hole densities and their mobilities*. The mobility of electrons and holes are weakly dependent on temperature. The

$$= 1.6 \times 10^{-19} (7.5 \times 10^{20} \times 0.135 + 3.0 \times 10^{11}) \text{ mho band is given by}$$

$$= 1.6 \times 10^{-19} (7.5 \times 10^{20} \times 0.135) \frac{\text{mho}}{\text{m}}$$

(Contribution of second term is negligible.)

$$= 0.162 \text{ mho/m}$$

\therefore Resistivity of doped semiconductor

$$\rho = \frac{1}{\sigma} = \frac{1}{0.162} = 6.172 \Omega \text{ m.}$$

Example 6.5

In a semiconductor it is observed that three-quarters of the current is carried by electrons and one quarter by holes. If at this temperature, the drift speed of electrons is three times that of the holes, determine the ratio of electrons to holes in the semiconductors.

Solution.

In a semiconductor, total current $I = I_e + I_h$

$$I_e = \frac{3}{4} I \text{ and } I_h = \frac{1}{4} I$$

also,

$$v_e = 3 v_h$$

$$I_e = e n A v_e \text{ and } I_h = e p A v_h$$

Here

$$\frac{I_e}{I_h} = \frac{e n A v_e}{e p A v_h} = \frac{n v_e}{p v_h} = \frac{n 3 v_h}{p v_h} = \frac{3 n}{p}$$

$$\frac{n}{p} = \frac{1}{3} \cdot \frac{I_e}{I_h} = \frac{1}{3} \cdot \frac{\frac{3}{4} I}{\frac{1}{4} I} = 1$$

$$\therefore n = p$$

Thus, the ratio of density of electrons to that of holes present in the semiconductor is unity.

Example 6.6

Find the resistivity of an intrinsic silicon doped with the donor impurity to the extent of 1 in 10^8 atoms. Given: density of silicon atoms = $5 \times 10^{28} \text{ m}^{-3}$, $m_e = 0.135$, $n_i = 1.5 \times 10^{16} \text{ m}^{-3}$.

Solution.

The density of donor atoms

$$N_D = \frac{5 \times 10^{28}}{10^8} = 5 \times 10^{20} \text{ m}^{-3}$$

$$np = n_i^2 = (1.5 \times 10^{16})^2 = 2.25 \times 10^{32} \text{ m}^{-3}$$

Since $n = N_D$,

$$\therefore p = \frac{n^2}{N_D} = \frac{2.25 \times 10^{32}}{5 \times 10^{20}} = 4.5 \times 10^{11} \text{ m}^{-3}$$

Since $n (= 5 \times 10^{20}) \gg p (= 4.5 \times 10^{11})$, clearly electrons are majority carriers and the material is *n*-type. The conductivity $\sigma = e n_e \mu_e = 5 \times 10^{20} \times 1.6 \times 10^{-19} \times 0.135 \text{ mho/m} = 10.8 \text{ mho/m}$.

∴ Resistivity,

$$\rho = \frac{1}{\sigma} = \frac{1}{10.8} \Omega \text{m} = 0.0926 \Omega \text{m}$$

Thus, we see that resistivity drops drastically to $0.0926 \Omega \text{m}$ from that of intrinsic semiconductor $2300 \Omega \text{m}$.

6.11 CARRIER CONCENTRATION IN INTRINSIC SEMICONDUCTORS

In intrinsic semiconductors, electrons in the conduction band and holes in the valence band constitute the charge carriers. Since these charge carriers are generated due to the breaking of covalent bonds, in the intrinsic semiconductors, the number of electrons is equal to the number of holes. At 0 K, since the covalent bonds are intact, the semiconductors act as insulators since hardly any charge carriers are present. As the temperature increases, the covalent bonds are broken and electron-hole pairs are created. We obtain below the expressions for the number of electrons in the conduction band per unit volume (n) and the number of holes in the valence band per unit volume (p).

6.11.1 Density of Electrons

Let dn be the number of electrons in the energy interval E and $E + dE$ in the conduction band,

$$dn = Z(E) F(E) dE \quad \dots(6.14)$$

where $Z(E) dE$ is the density of states in the energy interval E and $E + dE$ and $F(E)$ is the electron occupancy probability, i.e., the probability of a state of energy E being occupied by an electron.

If E_C is the energy corresponding to the bottom of the conduction band, to obtain the number of electrons in the conduction band, Eq. (6.14) has to be integrated from E_C to the top of the conduction band,

$$n = \int_{E_C}^{\infty} Z(E) F(E) dE \quad \dots(6.15)$$

The upper limit of integration is taken as infinity since the probability of electrons occupying the upper levels of the conduction band reduces to zero at infinity.

The density of states, i.e., the number of energy states per unit volume within the energy interval E and $E + dE$ is given by

$$Z(E) dE = \frac{4\pi}{h^3} (2m)^{3/2} E^{1/2} dE \quad \dots(6.16)$$

To account for the possibility of two electrons of opposite spin occupying any energy state corresponding to Pauli's exclusion principle, the above expression has been multiplied by 2 compared to the original expression. Since the electron moves in a periodic potential, its mass has to be

replaced by its effective mass m_e^* . Hence, the density of electrons in the conduction band is given by

$$Z(E) dE = \frac{4\pi}{h^3} (2m_e^*)^{3/2} E^{1/2} dE$$

Since the E starts at the bottom of the conduction band E_C ,

$$Z(E) dE = \frac{4\pi}{h^3} (2m_e^*)^{3/2} (E - E_C)^{1/2} dE \quad \dots(6.17)$$

We know the probability of an electron occupying an energy state E is given

$$F(E) dE = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)} \quad \dots(6.18)$$

where E_F is the energy of the Fermi level which is exactly at the middle of the forbidden energy gap in the intrinsic semiconductor, i.e.,

$$E_F = \frac{E_C + E_V}{2}$$

where, E_C is the energy of the bottom of the conduction band and E_V is the energy of the top of the valence band. Equation (6.18) can also be written as

$$F(E) dE = \left[1 + \exp\left(\frac{E - E_F}{kT}\right) \right]^{-1}$$

For all possible temperatures, $E - E_F \gg kT$,

$$F(E) dE \approx \exp\left(\frac{E_F - E}{kT}\right)$$

Therefore, Eq. (6.15) becomes

$$\begin{aligned} n &= \int_{E_C}^{\infty} \frac{4\pi}{h^3} (2m_e^*)^{3/2} (E - E_C)^{1/2} \exp\left(\frac{E_F - E}{kT}\right) dE \\ &= \frac{4\pi}{h^3} (2m_e^*)^{3/2} \int_{E_C}^{\infty} (E - E_C)^{1/2} \exp\left(\frac{E_F - E}{kT}\right) dE \\ &= \frac{4\pi}{h^3} (2m_e^*)^{3/2} \exp\left(\frac{E_F}{kT}\right) \int_{E_C}^{\infty} (E - E_C)^{1/2} \exp\left(-\frac{E}{kT}\right) dE \quad \dots(6.19) \end{aligned}$$

To evaluate this integral, let $E - E_C = x$

$$E = E_C + x \Rightarrow dE = dx$$

Substituting these, we get

$$n = \frac{4\pi}{h^3} (2m_e^*) \exp\left(\frac{E_F}{kT}\right) \int_0^{\infty} x^{1/2} \exp\left(-\frac{(E_C + x)}{kT}\right) dx$$

$$= \frac{4\pi}{h^3} (2m_e^*) \exp\left(\frac{(E_F + E_C)}{kT}\right) \int_0^\infty x^{1/2} \exp\left(-\frac{x}{kT}\right) dx \quad \dots(6.20)$$

Using gamma function it can be shown that

$$\int_0^\infty x^{1/2} \exp\left(-\frac{x}{kT}\right) dx = (kT)^{3/2} \frac{\pi^{1/2}}{2}$$

Hence,

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} \left(\exp \frac{E_F - E_C}{kT} \right) (kT)^{3/2} \frac{\pi^{1/2}}{2}$$

Thus, the **number of electrons per unit volume (or concentration of electron) in the conduction band** is given by

$$n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} \exp\left(\frac{E_F - E_C}{kT}\right) \quad \dots(6.21)$$

6.11.2 Density of Holes

Let dp be the number of holes in the valence band within the energy interval E and dE , given by

$$dp = Z(E) (1 - F(E)) dE \quad \dots(6.22)$$

where $Z(E) dE$ is the density of states in the energy interval E and $E + dE$ and $(1 - F(E))$ is the probability of existence of a hole. Here, it is important to note that since $F(E)$ is the probability of electron occupancy, $1 - F(E)$ gives the probability of the absence of an electron or the presence of a hole. Thus,

$$\begin{aligned} 1 - F(E) &= 1 - \left[\frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)} \right] \\ &= 1 - \left[1 + \left(\exp\left(\frac{E - E_F}{kT}\right) \right) \right]^{-1} \end{aligned}$$

Since

$$E - E_F \gg kT,$$

$$\therefore 1 - F(E) = \exp\left(\frac{E - E_F}{kT}\right) \quad \dots(6.23)$$

Density of holes in the valence band

$$Z(E) dE = \frac{4\pi}{h^3} (2m_h^*)^{3/2} E^{1/2} dE$$

Since E_V is the energy of the top of the valence band

$$Z(E) dE = \frac{4\pi}{h^3} (2m_h^*)^{3/2} (E_V - E)^{1/2} dE$$

To calculate the number of holes in the valence band, the above equation has to be integrated from $-\infty$ to the energy corresponding to the top of the conduction band E_V (for mathematical simplicity, the lowest energy is taken as $-\infty$). Thus, the number of holes in the valence band per unit volume is given by

$$\begin{aligned} p &= \int_{-\infty}^{E_V} \frac{4\pi}{h^3} (2m_h^*)^{3/2} (E_V - E)^{1/2} \exp\left(\frac{E - E_F}{kT}\right) dE \\ &= \frac{4\pi}{h^3} (2m_h^*) \exp\left(-\frac{E_F}{kT}\right) \int_{-\infty}^{E_V} (E_V - E)^{1/2} \exp\left(\frac{E}{kT}\right) dE \end{aligned}$$

To evaluate this integral, let $E_V - E = x$

$$E = E_V - x \Rightarrow dE = -dx$$

or

$$\begin{aligned} \int_{-\infty}^{E_V} (E_V - E)^{1/2} \exp\left(\frac{E}{kT}\right) dE &= - \int_{-\infty}^0 x^{1/2} \exp\left(\frac{E_V - x}{kT}\right) dx \\ &= \exp\left(\frac{E_V}{kT}\right) \int_0^\infty x^{1/2} \exp\left(-\frac{x}{kT}\right) dx \\ &= \exp\left(\frac{E_V}{kT}\right) (kT)^{3/2} \frac{\pi^{1/2}}{2} \quad (\text{using gamma } f_n) \end{aligned}$$

Hence,

$$p = \frac{4\pi}{h^3} (2m_h^*)^{3/2} \exp\left(\frac{E_V - E_F}{kT}\right) (kT)^{3/2} \frac{\pi^{1/2}}{2}$$

or

$$p = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} \exp\left(\frac{E_V - E_F}{kT}\right) \quad \dots(6.24)$$

Intrinsic Carrier Concentration

In intrinsic semiconductors, $n = p$.

Hence, $n = p \equiv n_i$ is called the **intrinsic carrier concentration** and is given by

$$n_i^2 = np = 4 \left(\frac{2\pi kT}{h^2} \right)^3 (m_e^* m_h^*)^{3/2} \exp\left(\frac{E_V - E_C}{kT}\right)$$

$$= 4 \left(\frac{2\pi kT}{h^2} \right)^3 (m_e^* m_h^*)^{3/2} \exp\left(\frac{-E_g}{2kT}\right)$$

where E_g is the forbidden energy gap. Hence,

$$n_i = 2 \left(\frac{2\pi kT}{h^2} \right)^{3/2} (m_e^* m_h^*)^{3/2} \exp\left(\frac{-E_g}{2kT}\right) \quad \dots(6.25)$$

Fermi Level in Intrinsic Semiconductor

In intrinsic semiconductors,

$$n = p$$

$$\text{or, } 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} \exp \left(\frac{E_F - E_C}{kT} \right) = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} \exp \left(\frac{E_V - E_F}{kT} \right)$$

$$\text{or, } (m_e^*)^{3/2} \exp \frac{E_F - E_C}{kT} = (m_h^*)^{3/2} \exp \frac{E_V - E_F}{kT}$$

$$\text{or, } \exp \frac{2E_F}{kT} = \left(\frac{m_h^*}{m_e^*} \right)^{3/2} \exp \left(\frac{E_V + E_C}{kT} \right)$$

Taking Logarithms on both sides

$$\frac{2E_F}{kT} = \frac{3}{2} \log \frac{m_h^*}{m_e^*} + \left(\frac{E_V + E_C}{kT} \right)$$

$$\text{or, } E_F = \frac{3kT}{4} \log \frac{m_h^*}{m_e^*} + \left(\frac{E_V + E_C}{2} \right) \quad \dots(6.26)$$

Assuming $m_h^* = m_e^*$ then

$$E_F = \frac{E_V + E_C}{2} \quad \dots(6.27)$$

Thus, in an intrinsic semiconductor, Fermi level is located at the middle of the valence and conduction bands and its position is independent of temperature (Fig. 6.11). However, since $m_h^* > m_e^*$, E_F is just above the middle and rises slightly with increasing temperature.

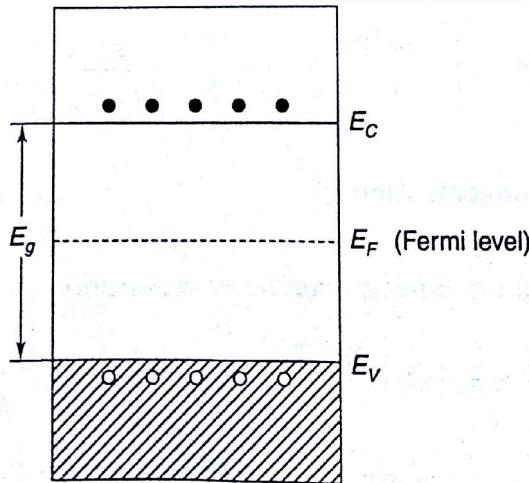


Fig. 6.11 Fermi level at the middle of valence and conduction bands.

6.12 ELECTRICAL CONDUCTIVITY: VARIATION WITH TEMPERATURE

We know that for a semiconductor, electrical conductivity σ is given by

$$\sigma = ne \mu_e + pe \mu_h$$

where μ_e and μ_h are the mobilities of electrons and holes respectively. Mobility is velocity acquired by the electron or hole per unit electric field.

For intrinsic semiconductor, $n = p \equiv n_i$

$$\sigma = n_i e (\mu_e + \mu_h)$$

\therefore Substituting for n_i from Eq. (6.25), we get

$$\sigma = (\mu_e + \mu_h) 2e \left(\frac{2\pi kT}{h^2} \right)^{3/2} \left(m_e^* m_h^* \right)^{3/4} \exp \left(- \frac{E_g}{2kT} \right) \quad \dots(6.28)$$

Thus, the electrical conductivity depends upon the negative exponential of the forbidden gap energy between the valence and conduction bands and on the mobilities of both holes and electrons. The mobilities are determined by the interaction of the electron or hole with lattice waves or phonons. In such a case μ_e and μ_h are both proportional to $T^{-3/2}$.

Hence, the electrical conductivity of an intrinsic semiconductor can be expressed as

$$\sigma_i = A \exp \left(- \frac{E_g}{2kT} \right) \quad \dots(6.29)$$

where A is a constant.

Taking logarithms on both sides, we have

$$\log \sigma_i = \log A - \frac{E_g}{2kT} \quad \dots(6.30)$$

A typical graph between $\frac{1}{T}$ and $\log \sigma_i$ is shown in Fig. 6.12. The graph indicates that the conductivity increases with temperature.

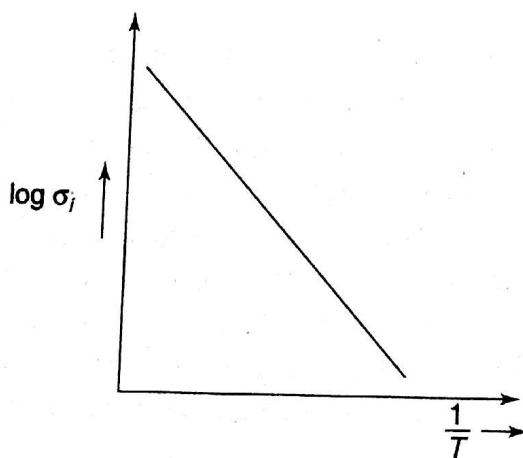


Fig. 6.12 Variation of electrical conductivity with temperature.

With increase temperature, more and more of the covalent bonds get broken and electrons and holes are generated, increasing the conductivity. Although, the carrier mobility decreases due to the increased mobility, the increased number of charge carriers overcome this and the net effect is the increase of σ with increasing temperature.

6.13 DRIFT AND DIFFUSION CURRENTS: EINSTEIN'S EQUATION

The net current that flows across a semiconductor has two components: (i) drift current and (ii) diffusion current.

6.13.1 Drift Current

In the absence of any externally applied electric field, the random motion of free carriers within a crystal does not result in a net transfer of charge since the charge transfer in one direction is balanced by movement of charge in the opposite direction. In other words, there is no flow of current. When a voltage is applied across the crystal each charge carrier experiences a force, electrons towards positive terminal and the holes towards the negative terminal. This results in a net flow of charge and the resulting current is called the *drift current*. The corresponding current densities due to drift of electrons and holes respectively are given by

$$J_n (\text{drift}) = n \mu_n e E$$

$$J_p (\text{drift}) = p \mu_p e E$$

Therefore, the total drift current density is given by

$$\begin{aligned} J(\text{drift}) &= J_n (\text{drift}) + J_p (\text{drift}) \\ &= n \mu_n e E + p \mu_p e E \end{aligned} \quad \dots(6.31)$$

Comparing this with Ohm's law $J = \sigma E$, gives

$$\sigma = n \mu_e e + p \mu_p e$$

For an intrinsic semiconductor, $n = p = n_i$. Therefore, the intrinsic conductivity is given by

$$\sigma_i = n_i e (\mu_n + \mu_p) \quad \dots(6.32)$$

For extrinsic semiconductors, only one term will be dominant as the current due to the minority carrier is negligible.

6.13.2 Diffusion Current

In addition to drift current, charge carrier in the semiconductors can also move by the *diffusion process*. The motion of the carrier by diffusion occurs when there is a non-uniform distribution of charged particles. The free electron density, at equilibrium, in a homogeneous semiconductor is uniform in the absence of any externally applied electric field. However, if excess carriers are introduced in a small region of the crystal either by injecting carriers or by generating carriers by heating or radiating, a *non-uniform distribution of charge carriers* is created. Ignoring the recombinations taking place, the *excess carriers move from the region of higher density to the regions of lower density tending to produce a uniform distribution*.

Let us assume that the concentration Δn of electrons varies in a distance Δx , in the limit as

$\Delta x \rightarrow 0$. Thus, a *concentration gradient* $\frac{dn}{dx}$ of the electrons exists in the material (ignoring the time

variation of n). The electron flux at any point due to diffusion is proportional to the concentration gradient at that point, i.e.,

$$\text{Diffusion electron flux} \propto \frac{dn}{dx} = D_n \frac{dn}{dx}$$

where, D_n is a proportionality constant called the *diffusing constant for electrons*. Following the Ficks's law which states the movement of charge carriers is in the direction of negative gradient. Therefore, the rate of flow electrons across unit area is equal to

$$-D_n \frac{dn}{dx}$$

This flow constitutes an *electron diffusion current density* and since conventional current is the rate of positive charge.

$$J_n (\text{diff}) = -e (\text{rate of flow of electrons across per unit area})$$

$$= e D_n \frac{dn}{dx} \quad \dots(6.33)$$

Similarly, if excess holes are created in a region, hole diffusion takes place and constitute a hole diffusion current given by

$$J_p (\text{diff}) = (+e) (\text{rate of diffusion of holes across per unit area})$$

$$= (+e) \left(-D_p \frac{dp}{dx} \right)$$

$$= -e D_p \frac{dp}{dx} \quad \dots(6.34)$$

where D_p is the hole diffusion coefficient.

If in a semiconducting material, an electric field E as well as a concentration gradient exists in a given direction say x , then the total current due to electrons is given by

$$J_{nx} = J_n (\text{drift}) + J_n (\text{diff})$$

$$= n_e \mu_n E + e D_n e \frac{dn}{dx} \quad \dots(6.35)$$

Similarly, total current density due to holes is given by

$$J_{px} = J_p (\text{drift}) + J_p (\text{diff})$$

$$= p e \mu_p E - e D_p \frac{dp}{dx} \quad \dots(6.36)$$

Thus, total current density is given by

$$J_x = J_n + J_p = e \left[\left(n \mu_n E + D_n \frac{dn}{dx} \right) + \left(p \mu_p E - D_p \frac{dp}{dx} \right) \right] \quad \dots(6.37)$$

The mobility μ express the ability of carriers drift while the diffusion constant D expreses the ability of carriers to diffuse.

6.13.3 Einstein's Equation

Both the drift and diffusion processes are dependent on the scattering which hinders the movement of charge carriers. Einstein showed that the parameters describing drift and diffusion, mobility μ and diffusion constant D respectitively, are directly related.

At equilibrium with no applied electric field, the free electron distribution is uniform and there is no net current flow. Any change in the state of equilibrium, which would lead to a diffusion current, creates an internal electric field and a drift current balancing the diffusion current component. Thus, in equilibrium

$$\Delta n e E \mu_n = e D_n \frac{\partial \Delta n}{\partial x} \quad \dots(6.38)$$

The force F on excess carriers restoring equilibrium is given by

$$F = (\Delta n) e E = \frac{e D_n}{\mu_n} \frac{\partial \Delta n}{\partial x} \quad \dots(6.39)$$

This force F on excess carriers is also dependent on the thermal energy of these carriers. Making an analogy between the excess carriers in a semiconductor and gas molecules in a gas container, the force corresponding to the pressure gradient is equal to $kT \frac{\partial(\Delta n)}{\partial x}$ as from the kinetic theory of gases, gas pressure is nkT , where n is the molecular concentration. Comparing this with Eq. (6.39), we get

$$kT = \frac{e D_n}{\mu_n}$$

$$\text{or } D_n = \frac{\mu_n kT}{e} \quad \dots(6.40)$$

This relation between diffusion coefficient and mobility of a charge carrier is known as *Einstein's equation*.

Similarly, for the holes, this relation is given by

$$D_p = \frac{\mu_p kT}{e} \quad \dots(6.41)$$

Hence, from Eqs. (6.40) and (6.41), we have

$$\frac{D_n}{D_p} = \frac{\mu_e}{\mu_p} \quad \dots(6.42)$$

Thus, knowing the other values, the diffusion coefficients of the charge carriers can be calculated. The calculated value of D_e for Si is $3.4 \times 10^{-3} \text{ m}^2/\text{s}$ and that of Ge is $9.9 \times 10^{-3} \text{ m}^2/\text{s}$ while that of D_p are $1.3 \times 10^{-3} \text{ m}^2/\text{s}$ (Si) and $4.7 \times 10^{-3} \text{ m}^2/\text{s}$ (Ge).

Example 6.7

The mobility of electrons in Si is $0.19 \text{ m}^2/\text{Vs}$, calculate the diffusion coefficient of electrons in Si at 310 K .

Solution.

We know

$$D_n = \frac{\mu_n kT}{e}$$

$$\mu_n = 0.19 \text{ m}^2/\text{Vs}, T = 310 \text{ K}$$

Here,

$$e = 1.6 \times 10^{-19} \text{ C}, k = 1.38 \times 10^{-23}$$

$$\therefore \text{Diffusion coefficient } D_n = \frac{0.19 \times 1.38 \times 10^{-23} \times 310}{1.6 \times 10^{-19}} \\ = 5.08 \times 10^{-3} \text{ m}^2/\text{s.}$$

6.14 GENERATION AND RECOMBINATION OF MINORITY CARRIERS

As the temperature of a semiconductor increases, covalent tetrahedral bonds are broken and free electrons are generated. Some of these free electrons may possess sufficient thermal energy to move from valence band to conduction band. A hole is created in the valance band for conducting every free electron moving to valence band. This is referred to as *electron-hole pair generation* (or production), as depicted in Fig. 6.13(a).

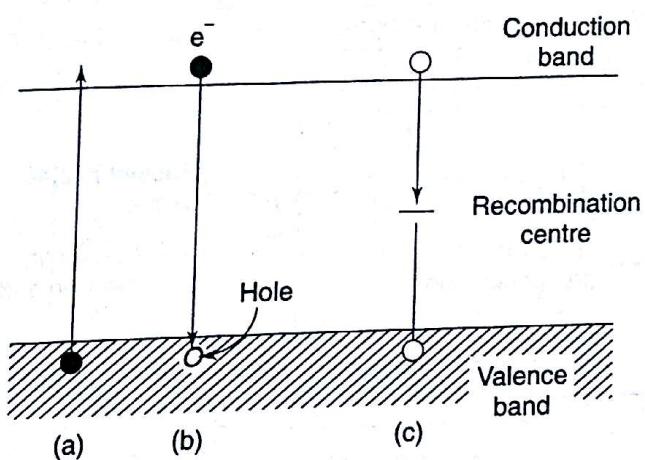


Fig. 6.13 (a) Electron-hole pair generation, (b) direct recombination, (c) recombination through a recombination centre.

In semiconducting materials, electron-hole pairs can be produced by light irradiation, if the frequency ν of the incident is high enough such that $h\nu > E_g$, where E_g is the forbidden energy gap. When the light is removed, the material returns to thermal equilibrium. This occurs by *electron-hole recombination* process. Recombination is said to have taken place, when one of the conducting electrons is bound again on a normal covalent tetrahedral site this is referred to as *band-to-band recombination* since the electron drops from the conduction band into the valence band in the energy band picture, as shown in Fig. 6.13(b). Band-to-band recombination generally results in the emission of photons with energy equal to that of the semiconductor energy gap. In gallium arsenide this type of recombination is common.

In Ge and Si, recombination occurs via a *recombination centre*, which are located at the centre of the energy gap. These levels are introduced by impurity atoms such as Cu and Au.

This type of recombination process may be considered to occur as follows. When a hole jumps from valence band to the recombination centre (also called trap) and an electron from valence band drops to this level, *annihilation* takes place. It may also be considered an electron from the conduction band dropping into a hole in the valence band using recombination level as a stepping stone, as shown in Fig. 6.13(c).

Non-uniformity in periodic structure can occur at an interface between two crystals. Such non-uniformity disrupt the periodic nature of the electric field within the crystal causing regions which become centres of trap or capture of free charge carriers. In the energy band model these disturbances in the electric field create energy levels in energy gap range which has high probability of capturing an electron, a hole or both of them (Fig. 6.14).

These energy levels approaching the conduction band energies are termed *electron traps*, as they have high probability of capturing free electrons. Similarly, those levels near valence band levels are called *hole traps*, having a high probability of capturing a hole. During its life as a carrier, an electron or hole gets trapped several times and being freed to the adjacent band by energy absorption. While trapped the electrons and holes do not contribute to the conduction process. The average time that an electron or hole remains free after generation is known as its lifetime (τ).

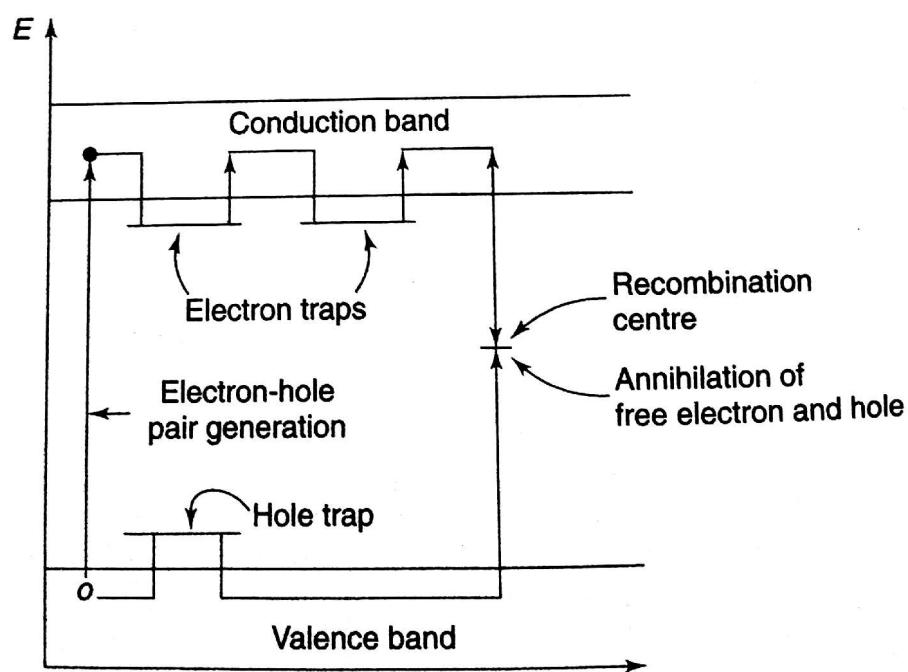


Fig. 6.14 Band model representation of generation and recombination in a semiconductor.

∴

$$R_H = \frac{37 \times 10^{-6} \times 10^{-3}}{20 \times 10^{-3} \times 0.5} = 3.7 \times 10^{-6} \text{ C}^{-1}\text{m}^3$$

6.16 FORMATION OF P-N JUNCTION DIODE

A *p*-type or *n*-type silicon (or germanium) can be grown by adding suitable and controlled amount of impurity in the melt of pure silicon (or germanium). The crystal grown are cut into thin slices called wafer. Semiconductor devices such as diode, transistor, field effect transistor (FET), etc. are grown on these wafers.

If on a wafer of *n*-type silicon, a thin film of trivalent material, say aluminium, is placed and heated to a high temperature ($\approx 575^\circ \text{C}$), aluminium diffuses into silicon. Consequently, a *p*-type semiconductor is formed on an *n*-type semiconductor. The boundary (or surface of contact or region of transition between *p*-type semiconducting materials) is called the *p-n* junction. A *p-n* junction can also be grown by diffusing a pentavalent material, say phosphorus, into a *p*-type semiconductor.

The wafer on which *p-n* junction are grown, is cut into small pieces. The simplest semiconductor device is *p-n* junction diode. A *p-n* junction diode consists of *p* and *n* semiconducting regions on a single wafer encapsulated in a casing with electrical contact coming out from *p* and *n* regions.

There are numerous ways of forming *p-n* junction and it is also possible to form more than one junction (e.g., *pnp* and *npn*) on the same wafer. We shall not go here into the details of these processes.

Figure 6.18(a) shows a *p-n* junction diode, *p*-side is also known as anode and *n*-side cathode. The symbolic representation of a *p-n* junction diode is shown in Fig. 6.18(b). The arrow indicates the direction of conventional current flow.

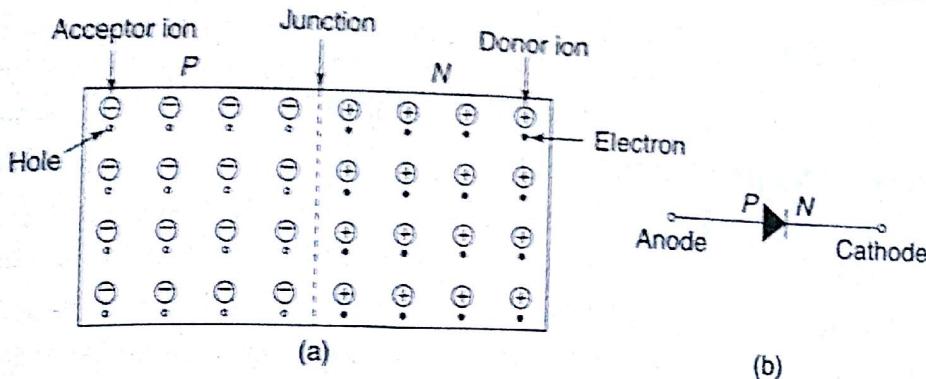


Fig. 6.18 (a) Formation of a p - n junction. (b) Symbol of a p - n junction diode.

6.17 DEPLETION LAYER AND BARRIER POTENTIAL IN A P-N JUNCTION DIODE

We discuss below the physics involved in a p - n junction diode.

In a p - n junction diode, the p -region has high concentration of holes and the n -region that of electrons. The moment p - n junction is formed, holes from the p -region start diffusing across the junction into the n -region while electrons from the n -region diffuse across the junction into the p -region. When an electron diffuses into p -region, it (the electron) falls into a vacancy, in other words, it recombines with a hole. This process is called *recombination*. This recombination results in the production of an ionized acceptor atom, as it has accepted an electron. The ionized acceptor atom becomes negatively charged and is immobile. In the p -region, in the immediate vicinity of the junction, immobile excess negative charges are formed.

Similarly, holes from the p -region recombine with electrons in n -side on crossing the junction. This results in the formation of immobile excess positive charges in the vicinity of the junction on the n -side.

These layers of (immobile) charge create an *electric field*, which exerts a force on the electrons and holes and thus opposes their further diffusion across the junction (Fig. 6.19). The electric field becomes strong enough, as diffusion proceeds, to stop it. Due to this field, there is a potential at the junction (with n side at higher potential), known as *barrier potential* (V_B). This is so called because this potential acts as a barrier for charge motion in the diffusion process. The magnitude of the barrier potential is 0.3 V for germanium junction diode and about 0.7 V for silicon junction diode. Besides the nature of the crystal, the amount of doping and temperature of the crystal are the other factors which determine the magnitude of V_B .

Because of inter-diffusion, the region in the vicinity of the junction has very low concentration of charge carriers. This region is called *depletion region*. The thickness of this region is about $1 \mu\text{m}$ (10^{-6} m). The barrier potential is the potential difference across the depletion with n -side of the depletion region at higher potential (Fig. 6.19). A very large electric field is set up across the depletion region. The approximate strength of the electric field is

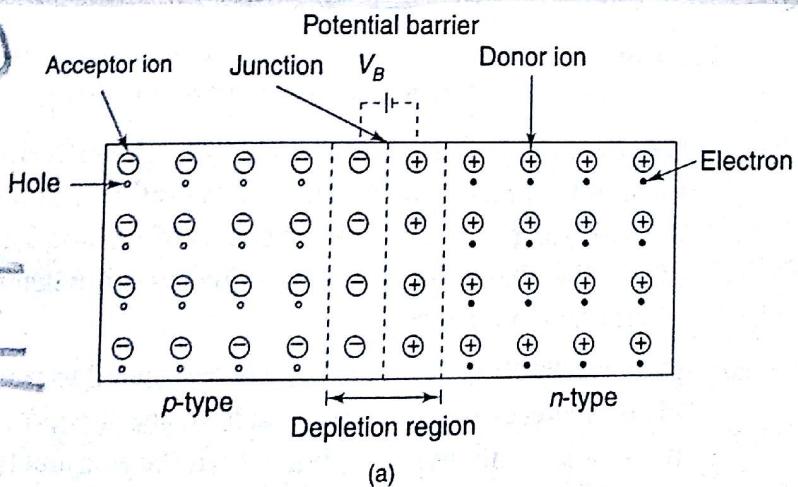


Fig. 6.19

$$E = \frac{\text{Barrier potential}}{\text{Thickness of depletion region}} = \frac{0.7 \text{ V}}{10^{-6} \text{ m}} = 7 \times 10^3 \text{ Vm}^{-1}$$

6.18 BIASING OF P-N JUNCTION DIODE

Applying a suitable external potential difference to a *p-n* junction diode is called the *biasing*. There are two ways in which a *p-n* junction diode can be biased. Both of these are discussed below.

- (i) **Forward Biasing:** When a battery is connected to a *p-n* junction diode in such a way that positive of the battery is connected to *p*-side and negative to *n*-side, the junction diode is said to be forward biased.

If the diode is forward biased, the externally applied voltage creates an electric field across the *p-n* junction that is opposite to the field due potential barrier (V_B) (Fig. 6.20). Therefore, the potential across the junction decreases, i.e., potential barrier is lowered and the diffusion of electrons and holes across the junction thereby increases, resulting in a current in the circuit. In case the forward bias (V) is greater than the barrier potential (V_B), charge carriers, i.e., electrons and holes diffuse easily resulting in a sharp increase in the current through the junction diode.

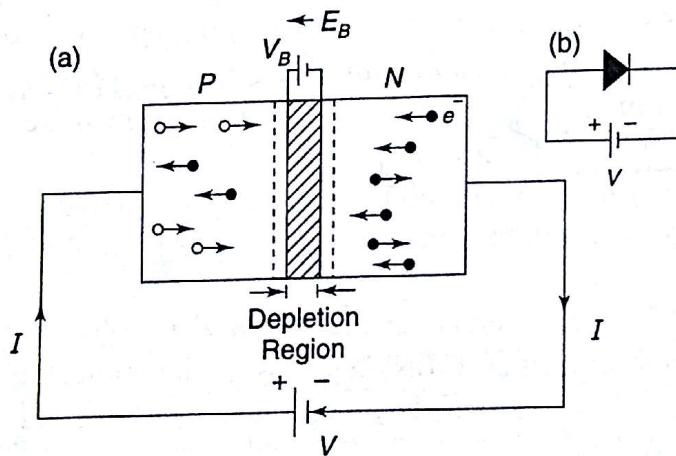


Fig. 6.20 A forward biased *p-n* junction diode. The dotted lines indicate original (unbiased) depletion layer. V_B —barrier potential, V —applied potential.

Due to motion of majority carrier, that is, holes from *p*-region and electrons from *n*-region, towards the junction in forward bias condition the thickness of the depletion region decreases or depletion region shrinks. A reduced depletion region offers a low resistance to the flow of current. The current flowing in the circuit when the junction diode is forward biased is also known as forward current.

- (ii) **Reverse Biasing:** If a battery is connected to *p-n* junction diode with positive terminal of its (battery) joined to the *n*-side of the junction diode and negative terminal joined to the *p*-side of the junction diode, then the *p-n* junction diode is said to be reverse biased. In case of reverse biasing, the externally applied potential and barrier potential are in same direction. Due to this thickness of depletion region increases or resultant barrier potential increases inhibiting the diffusion of holes and electrons across the junction (Fig. 6.21). The resistance offered by the depletion region becomes very high and consequently current drops to a negligibly small value. However, a very small amount of current flows due to

the motion of minority carriers, i.e., holes in *n*-region and electrons in *p*-region. This current is called *reverse current*. Potential barrier in the junction region opposes the flow of majority carriers but accelerates minority carriers.

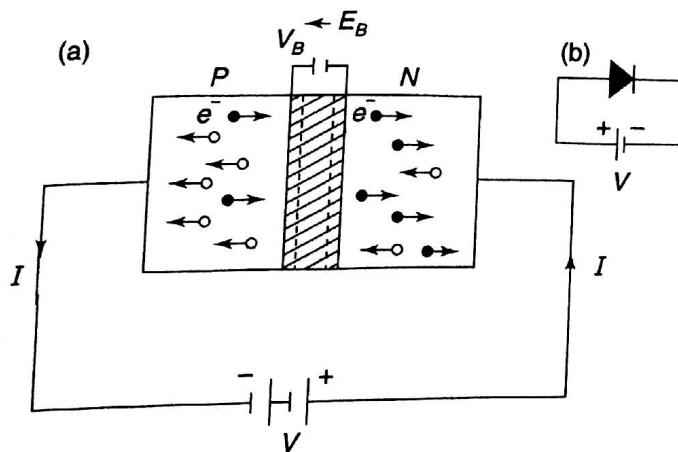


Fig. 6.21 A reverse-biased *p-n* junction diode. The dotted lines indicate original depletion region.

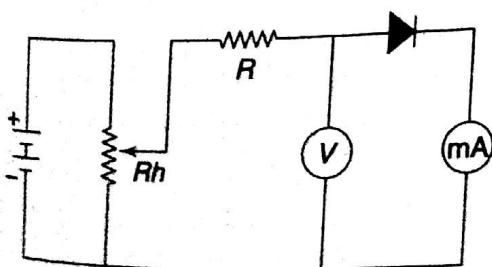
6.19 CHARACTERISTICS OF A P-N JUNCTION DIODE

The relation between applied voltage (*V*) and the resulting current (*I*), expressed graphically, is known as characteristic curve of a device. In a *p-n* junction diode the characteristic curve in forward bias condition differs drastically from that in reverse bias condition. We discuss the two characteristics below.

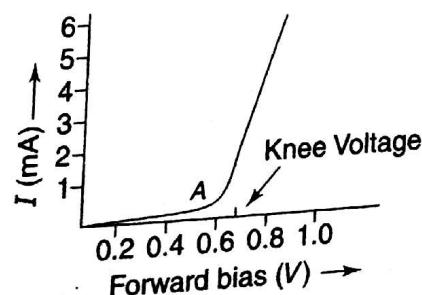
6.19.1 Forward Bias Characteristics

Figure 6.22(a) shows the circuit diagram for obtaining the characteristic curve of a forward biased *p-n* junction diode. The battery is connected to the diode through a rheostat (or potentiometer) so that the voltage applied to the diode can be changed. The voltmeter across the diode measures the voltage across the diode and the milliammeter measures the current in the diode. The voltage across the diode is increased in small steps, say 0.1 V, and the corresponding current is noted. A typical forward characteristic curve for a silicon diode ($V_B \approx 0.7$ V) is shown in Fig. 6.22(b).

As shown in Fig. 6.22(b), the current increases very slowly across the diode till a certain voltage, a characteristic of the diode, is reached. After this characteristic voltage, the diode current increases rapidly, even for very small increase in the diode bias voltage. This voltage is called the *threshold voltage* or *cut-in voltage* or *knee voltage*. The value of this voltage is about 0.3 V for a germanium diode and 0.7 V for a silicon diode.



(a) Circuit diagram for characteristic curve of a forward biased *p-n* junction diode.



(b) Characteristic curve of a forward biased *p-n* junction diode.

Fig. 6.22

To understand the characteristic curve, it is important to note that till the applied potential is less than the barrier potential, there is very small current because the barrier potential exists. As the applied potential is increased the barrier potential decreases and initially current increases slowly. When the applied potential becomes equal or exceeds the barrier potential, the thickness of depletion region becomes negligible. Electrons from n -region and holes from p -region, move across the junction without encountering any appreciable resistance. As a consequence, a relatively large current flows through the diode.

6.19.2 Reverse Bias Characteristics

Figure 6.23(a) shows the circuit diagram for obtaining the characteristic curve of a reverse biased $p-n$ junction diode. Here a microammeter (μA) is used. A typical reverse characteristic curve is shown in Fig. 6.23(b).

When the diode is reverse biased, the reverse bias voltage produces an extremely small current, about a few microamperes (μA) which remains nearly constant. This current is also sometimes referred to as *leakage current*. However, when the applied reverse voltage reaches a characteristic voltage called the *breakdown voltage* the current suddenly increases to a large value. The breakdown voltage is also called the *peak-inverse voltage* of the diode. A normal $p-n$ junction diode (unlike Zener diode, discussed later) is not operated in the reverse bias beyond the breakdown voltage.

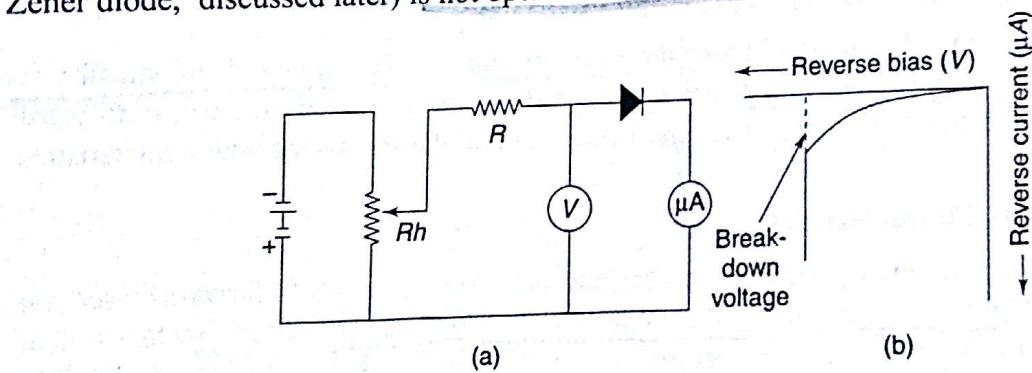


Fig. 6.23 (a) Circuit diagram for characteristics of a reverse biased $p-n$ junction diode
 (b) Characteristic curve of a reverse biased $p-n$ junction diode.

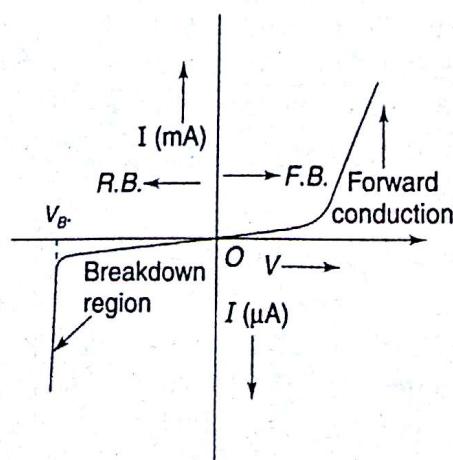


Fig. 6.24 A typical complete diode characteristic in the forward and reverse region (not to scale).

6.19.3 Resistance of Junction Diode

The current-voltage curve of a *p-n* junction diode is not a straight line, i.e., it does not obey Ohm's law and thus it is a *non-ohmic device*. Further, the resistance offered by the junction diode depends upon the applied voltage due to the characteristic curve not being a straight line.

The d.c. resistance ($R_{d.c.}$) of a *p-n* junction diode is the ratio of the applied voltage (V) and the resulting current (I), that is,

$$(R_{d.c.} = \frac{V}{I}) \text{ } gnp$$

The d.c. resistance is not a very useful parameter. The dynamic or a.c. resistance ($R_{a.c.}$) is the most commonly used parameter. The dynamic resistance of a junction diode is defined as the ratio of small change in voltage (ΔV) to the small change in current produced (ΔI). That is,

$$(R_{a.c.} = \frac{\Delta V}{\Delta I}) \text{ } gmp$$

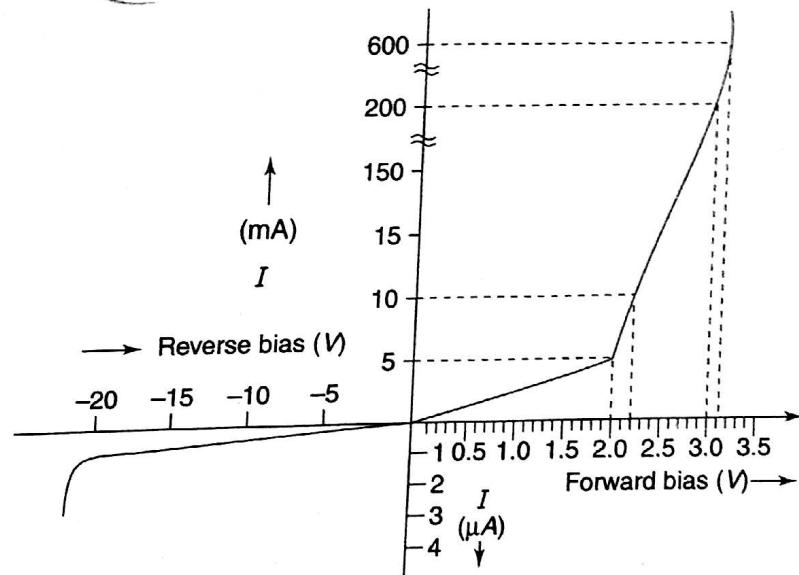


Fig. 6.25

The region of the characteristic curve where the dynamic resistance is almost independent of the applied voltage is called the linear region of junction diode.)

Example 6.13

The I-V characteristic of a *p-n* junction diode is shown in Fig. 6.25. Find the approximate dynamic resistance of the *p-n* junction when (i) a forward bias of 2 volts is applied, (ii) a forward bias of 3 volts is applied.

Solution.

- (i) The current at 2 V is 5 mA and at 2.2 V it is 10 mA. The dynamic (or a.c.) resistance in this region is

6.20 ZENER DIODE

In Fig. 6.27, the $I-V$ characteristic of a $p-n$ junction diode including the diode which are meant to be operated in reverse bias condition, such as a Zener diode, is shown. As seen in the figure, if the reverse bias voltage across a $p-n$ junction diode is increased, at a particular voltage called *breakdown voltage*, the (reverse) current suddenly increases to a large value. The Zener diode is a specially designed junction diode to operate in the breakdown region without getting damaged. The symbol of a Zener diode is shown in Fig. 6.28(a). Such a diode can be used as a *constant-voltage* device, as shown in Fig. 6.28(b).

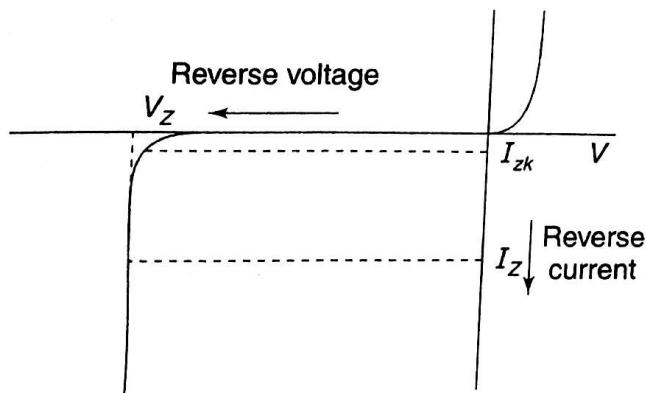


Fig. 6.27 $V-I$ characteristic of a Zener diode.

The voltage at which the breakdown occurs is known as the zener (or breakdown) voltage (V_z) for the Zener diode. The breakdown voltage depends upon the extent of doping. A Zener diode is comparatively heavily doped so that the breakdown occurs at a lower voltage. Zener diodes with breakdown voltage between 5 V to 200 V are commercially available.

When the reverse voltage across the Zener diode is equal or more than its breakdown V_z , the current increases sharply. After the breakdown, a small change in voltage produces a very large change in current or in other words corresponding to a large change in voltage takes place. This property is utilized in using Zener diode as *voltage regulator*.

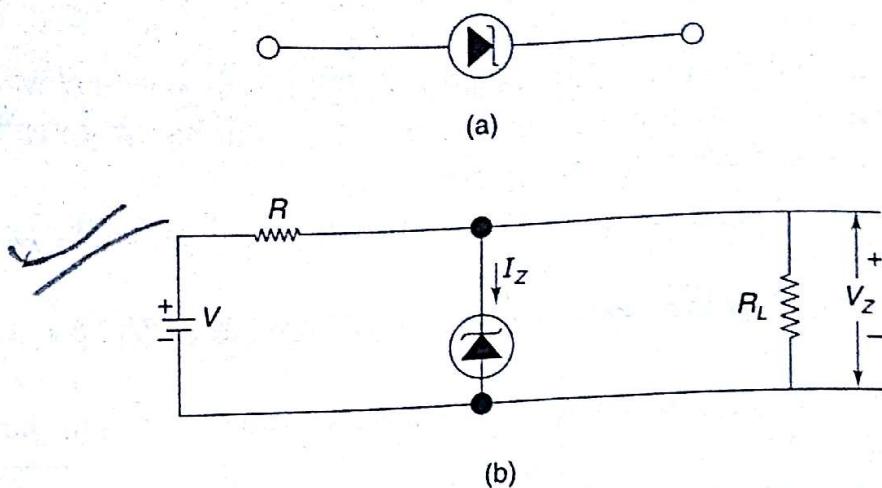


Fig. 6.28 (a) Symbol of a Zener diode (b) Zener diode as a voltage regulator.

6.20.1 Zener Diode as Voltage Regulator

A Zener diode can be used as a constant-voltage device or voltage regulator using a circuit given in Fig. 6.28(b). When the input voltage V and resistor R is such that voltage across the Zener diode is equal to or greater than its breakdown voltage V_Z , the Zener diode operates in the breakdown region. The voltage across the load R_L is the same as across the diode, V_Z and the diode current is I_Z . The diode now can regulate (or keep constant) the load voltage even if there is a variation in the load current and supply (input) voltage. If there is a change in load voltage or supply voltage, the diode current adjusts itself (increase or decrease) so as to maintain a nearly constant load voltage. The diode continues to act as a voltage stabilizer until the circuit changes require the diode current to fall to I_{ZK} , near the knee of the diode $I-V$ curve. The upper limit of the diode current is determined by the power-dissipation capability of the diode.

6.20.2 Difference Between Zener Breakdown and Avalanche Breakdown

In normal $p-n$ junction diodes, the breakdown takes place by avalanche breakdown. The avalanche breakdown takes place as discussed below. When a thermally generated electron (part of reverse current) falls down the junction barrier and acquires energy from the applied potential, it may collide with a crystal ion breaking the covalent bond and thus creating a new electron-hole pair. These carriers in turn acquire sufficient energy to collide with another crystal ion generating another electron-hole pair. This cumulative process leads to avalanche multiplication. This results in a large reverse current in the diode and the diode is to be in the region of *avalanche breakdown*.

In Zener diode, the breakdown takes place by *Zener breakdown* which is different from avalanche breakdown. A Zener diode is comparatively heavily doped. Because of the existence of a comparative strong electric field at the junction, a sufficiently strong force may be exerted on a bound electron, forcing one of its covalent bond, generating a new electron-hole pair and so increasing the reverse current when this process continues, the reverse current increases sharply. This is known as *Zener breakdown*. Zener breakdown occurs at an electric field of approximately $2 \times 10^{-7} \text{ Vm}^{-1}$. This value of the field is reached for voltage below 6 V for heavily doped diodes. For lightly doped diodes the breakdown voltage is higher and the avalanche multiplication is a predominant effect.