

# INTRINSIC SEMICONDUCTORS

## 10.1 Introduction

Semiconductors are group of materials having resistivity between those of metals and insulators. The resistivity of semiconductors lie in the range of  $10^{-6}$  to  $10^8 \Omega\text{m}$ .

The interesting feature of semiconductors is that, they are bipolar, i.e., current conduction take place by two charge carriers namely electrons and holes. Semiconductors are especially important because, varying condition like temperature and impurity can easily alter their conductivity.

Application importance of semiconductors results from the fact that, they can be conductors as well as insulators. The major applications of semiconductors are in the manufacture of electronic devices and integrated circuits.

In this chapter and in the next chapter, the different types of semiconductors and their mechanism of conduction will be studied.

## 10.2 Semiconductors

Semiconductors are solid materials having electrical resistivity in between those of conductors and insulators. Commonly used semiconducting materials are Si, Ge, GaAs and InP.

### 10.2.1 Properties of semiconductors

1. The resistivity of semiconductors is usually high.
2. The semiconductors have negative temperature coefficient of resistance.  
[This refers to the decrease in resistivity of a semiconductor with rise of temperature].
3. Semiconductors are metallic in nature. But are generally hard and brittle.
4. At 0K, semiconductors behave as insulators.
5. In semiconductors both electrons and holes are the charge carriers.
6. Semiconductors have a filled valence band and empty conduction band at 0K.

## 10.3 Types of Semiconductors

The semiconductors can be classified into various types based on different characteristics. In the following section the classification of semiconductors based on the number of constituting elements and on purity aspects are explained.

### 10.3.1 Elemental and compound semiconductors

Based on the number of constituting elements, there are two general classifications of semiconductors.

1. Elemental semiconductors.
2. Compounds or Compound semiconductors.

#### Elemental semiconductors

*Semiconductors which are composed of single species of atoms are called elemental semiconductors. Elemental semiconductors are found in group IV of the periodic table.*

*Examples :* Si and Ge.

#### Compound semiconductors

*Semiconductors which are composed of two or more different species of atoms are called compounds or compound semiconductors.*

These semiconductors can be formed by combining different group elements from periodic table.

#### III - V Compounds

*Compound semiconductors formed by elements from third and fifth groups are called III - V compounds.*

#### II - VI Compounds

*Compound semiconductors formed by elements from second and sixth groups are called II - VI compounds.*

#### List of a few elements from periodic table

|          | Groups |     |    |    |    |
|----------|--------|-----|----|----|----|
|          | II     | III | IV | V  | VI |
| Elements | Zn     | B   | C  | P  | S  |
|          | Cd     | Al  | Si | As | Te |
|          |        | Ga  | Ge | Sb |    |
|          |        |     | Pb |    |    |

*A compound semiconductor consisting of two elements is called binary compound.*

*Examples :*

- (1) GaAs, GaP, InP, InAs and InSb.

These compounds are formed by combining group III and V elements of periodic table.

- (2) ZnS, CdS, CdTe, ZnTe.

These compounds are formed by combining elements of II and VI group from the periodic table.

*Compound semiconductors consisting of three and four elements are called ternary compounds and quarternary compounds respectively.*

**Examples of ternary compounds** GaAsP, AlGaAs.

**Examples of quarternary compounds** AlGaAsP, InGaAsP.

The major advantage of compound semiconductors over elemental semiconductors is the availability of a wide range of energy gaps and the high mobility of charge carriers.

The compounds find a wide range of optoelectronic applications like fiber optic communication, optical storage, compact disc, indicators in appliances, traffic signals, commercial displays, laser printers etc.

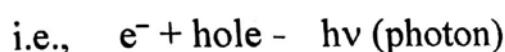
### 10.3.2 Direct band gap and indirect band gap semiconductors

Based on the type of energy emission the semiconductors can be of two groups.

1. Direct band gap semiconductors.
2. Indirect band gap semiconductors.

#### Direct band gap semiconductors

In a direct band gap semiconductor such as GaAs, AlAs and InP, when an excited electron falls back into the valence band, the electrons and holes recombine to produce light energy.



This process is known as radiative recombination. Also called spontaneous emission.

These direct band gap semiconductors are used to make LED's and lasers of different colours.

#### Indirect band gap semiconductors

In an indirect band gap semiconductor such as Si, Ge and GaP, when an excited electron falls back into the valence band, the electrons and holes recombine to generate heat and is dissipated within the material.

i.e.,  $e^- + \text{hole} \rightarrow \text{phonon}$ . This process is known as non-radiative recombination.

### 10.3.3 Intrinsic and extrinsic semiconductors

Based on purity, semiconductors are of two types.

1. Intrinsic semiconductors.
2. Extrinsic semiconductors.

In the following section the intrinsic semiconductors are discussed in detail. The details of extrinsic semiconductors will be discussed in the next chapter.

## 10.4 Intrinsic Semiconductors

 The intrinsic semiconductors are pure semiconductor materials. These semiconductors possess poor conductivity. The elemental and compound semiconductor can be of intrinsic type.

The energy gap between valence band and conduction band is relatively very small. Hence, at room temperature, some electrons may possess enough thermal energy to cross over the band gap and enter the conduction band. Thus, the excited electrons leave behind a vacancy which may be filled by another electron in the valence band. The vacancy produced in the valence band due to the electron excitation is called a hole.

In intrinsic semiconductor for every conduction electron promoted to the conduction band, there is a hole in the valence band. Holes and electrons created in this way are known as intrinsic charge carriers. Thus, in an intrinsic semiconductor.

$$n_e = n_h$$

i.e., The density of electrons = The density of holes.

In an intrinsic semiconductor, when an electron moves to fill a hole, another hole is created at the original electron source. Consequently, the holes appear to act as positively charged electron and carry an electrical charge.

When a voltage is applied to the material, the electrons in the conduction band accelerate towards the positive terminal and the holes in the valence band move towards the negative terminal. Hence, current conduction takes place due to the movement of both the charge carriers electrons and holes.

Thus, the expression for conductivity is given by

$$\sigma_i = n_e e \mu_e + n_h e \mu_h$$

or       $\sigma_i = n_i e (\mu_e + \mu_h)$

where  $n_e = n_h = n_i$  is called the intrinsic carrier concentration and  $\mu_e$ ,  $\mu_h$  are the mobilities of electrons and holes respectively.

### 10.5 Carrier Concentration in an Intrinsic Semiconductor

In general, the number of charge carries per unit volume of the material is called carrier concentration.

At 0K in an intrinsic semiconductor, the valence band is completely filled and the conduction band is completely empty. The fermi level lies exactly midway between the valence band and conduction band as shown in figure 10.1.

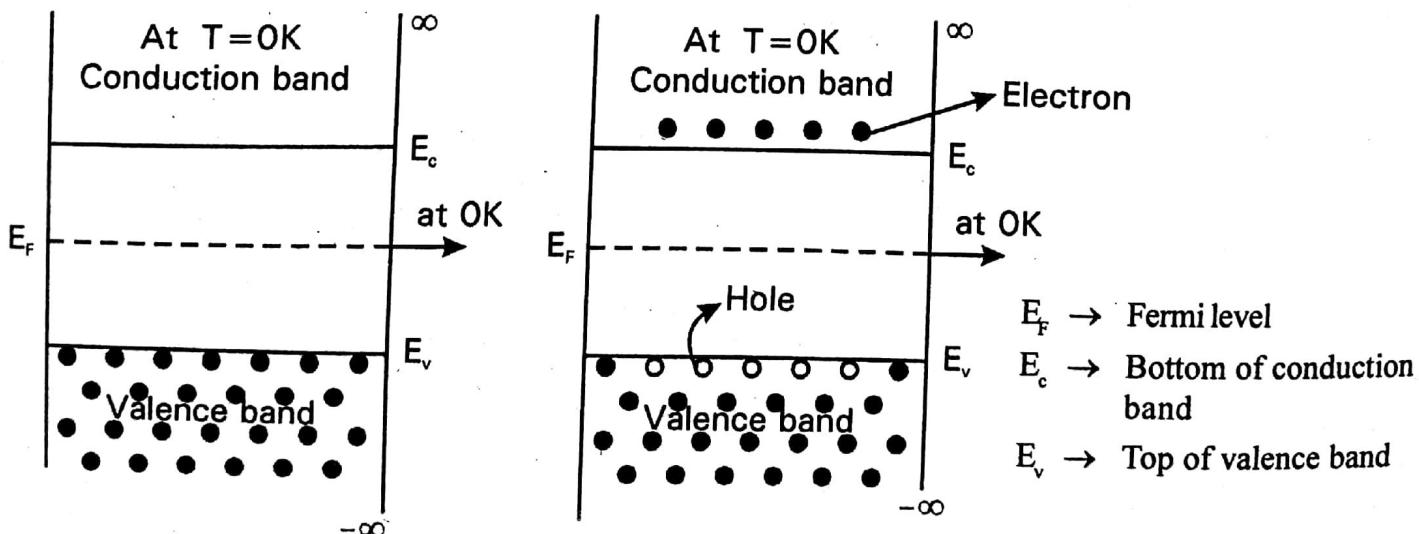


Figure 10.1 : Energy band diagram for an intrinsic semiconductor at  $T=0K$  and  $T>0K$

As the temperature of the semiconductor is increased, electrons from the valence band get thermally excited to the conduction band. These electrons in the conduction band behave like a free particle with an effective mass  $m_e^*$ .

Similarly, the holes created by these electrons in the valence band also behave like a free particle with an effective mass  $m_h^*$ . Hence, the electrons in the conduction band and holes in the valence band both contribute to electrical conduction.

**Note :** • **Effective mass :** It is a parameter that takes into account the effect of internal forces in the crystal. This parameter relates the acceleration of an electron in the conduction band of a solid to an external force.

### 10.5.1 Expression for density of electrons in conduction band

The carrier density in a semiconductor, can be obtained by integrating the product of the density of states  $Z(E)dE$  and the probability function i.e., the fermi function  $f(E)$  over all possible states.

$$\text{i.e., } n_e = \int_{E=0}^{E_{\max}} Z(E)dE f(E) \quad \text{--- [1]}$$

Thus, the density of electrons  $n_e$  in the conduction band can be evaluated by integrating the above expression from the bottom of the conduction band labeled  $E_c$  to the top of the conduction band labelled  $\infty$  as shown in figure 10.1.

∴ Density of electrons in the conduction band is

$$n_e = \int_{E_c}^{\infty} Z(E)dE f(E) \quad \text{--- [2]}$$

Since, the fermi function becomes zero at higher energies, it becomes difficult to locate the actual top levels of the conduction band. Hence for this reason, the upper limit is taken as  $\infty$ .

The density of states with energy interval  $E$  and  $E + dE$  for an electron which behaves as a free particle with effective mass  $m_e^*$  is given by

$$Z(E)dE = \frac{\pi}{2} \left( \frac{8m_e^*}{h^2} \right)^{3/2} E^{1/2} dE \quad \text{--- [3]}$$

[The above expression is written based on the general expression for density of states, refer section 9.5 with mass  $m$  replaced by  $m_e^*$ .]

The energy  $E$  for an electron in the conduction band, now becomes equal to  $E - E_c$ .

Hence,  $E$  in equation (3) must be replaced by  $E - E_c$ .

$$\therefore Z(E)dE = \frac{\pi}{2} \left( \frac{8m_e^*}{h^2} \right)^{3/2} (E - E_c)^{1/2} dE \quad \text{--- [4]}$$

**Note :** • The equation (3) has been obtained by taking  $E = 0$  for the bottom of the conduction band as reference. But now, since we are considering the energy value of the bottom of the conduction band to be  $E_c$ , the energy  $E$  for an electron in the conduction band is equal to  $E - E_c$ .

Therefore, substituting equation (4) in equation (2) we get,

$$n_e = \frac{\pi}{2} \left( \frac{8m_e^*}{h^2} \right)^{3/2} \int_{E_c}^{\infty} (E - E_c)^{1/2} dE f(E) \quad \text{--- [5]}$$

But, we know the probability function for the occupancy of an electron is given by

$$f(E) = \frac{1}{1 + e^{\left(\frac{E-E_F}{k_B T}\right)}} \quad \text{--- [6]}$$

For all temperatures, the energy required by an electron to move from the valence band to the conduction band is always greater than  $k_B T$ .

Let us assume, at room temperature  $E_F$  is lower than  $E_c$  by atleast a few  $k_B T$  ( $\geq 4 k_B T \approx 0.01 \text{ eV}$ )

$$\text{i.e., } E - E_F \gg k_B T$$

Hence, if  $(E - E_F) \gg k_B T$ , then the term 1 in the denominator of equation (6) can

be neglected (since  $\frac{E - E_F}{k_B T} \gg 1$  then,  $e^{\left(\frac{E-E_F}{k_B T}\right)}$  is also  $\gg 1$ ).

$$\therefore f(E) = \frac{1}{e^{\left(\frac{E-E_F}{k_B T}\right)}}$$

$$f(E) = e^{-\left(\frac{E-E_F}{k_B T}\right)}$$

$$\text{or } f(E) = e^{\left(\frac{E_F-E}{k_B T}\right)}$$

---- [7]

Therefore, substituting for  $f(E)$  from equation (7) in equation (5) we get,

$$n_e = \frac{\pi}{2} \left( \frac{8m_e^*}{h^2} \right)^{3/2} \int_{E_c}^{\infty} (E - E_c)^{1/2} e^{\left(\frac{E_F-E}{k_B T}\right)} dE \quad \text{--- [8]}$$

To solve the above integration, let us define

$$E - E_c = x k_B T \quad \text{--- [9]}$$

$$\therefore E = E_c + x k_B T \quad \text{--- [10]}$$

on differentiating the above equation, we get

$$dE = dx k_B T \quad \text{--- [11]}$$

Based on equation (9), the integral limits for equation (8) also get changed accordingly as follows.

When  $E = E_c$   
 $E_c - E_c = x$   
or  $x = 0$   
(Lower limit)

Similarly, when  $E = \infty$   
 $\infty - E_c = x$   
or  $x = \infty$   
(Upper limit)

Therefore, equation (8) becomes, (substituting equations (9), (10), (11) and limits)

$$n_e = \frac{\pi}{2} \left( \frac{8m_e^*}{h^2} \right)^{3/2} \int_0^{\infty} (x k_B T)^{1/2} e^{-\frac{(E_F-x k_B T-E_c)}{k_B T}} k_B T dx$$

$$n_e = \frac{\pi}{2} \left( \frac{8m_e^*}{h^2} \right)^{3/2} (k_B T)^{1/2} (k_B T)^1 e^{\left( \frac{E_F-E_c}{k_B T} \right)} \int_0^{\infty} x^{1/2} e^{-x} dx$$

$$n_e = \frac{\pi}{2} \left( \frac{8m_e^* k_B T}{h^2} \right)^{3/2} e^{\left( \frac{E_F-E_c}{k_B T} \right)} \frac{\sqrt{\pi}}{2}$$

[Since  $\int_0^{\infty} x^{1/2} e^{-x} dx = \frac{\sqrt{\pi}}{2}$ . This is called the gamma function.]

Therefore, on simplifying the above equation we get,

$$\text{or } n_e = 2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2} e^{\left( \frac{E_F-E_c}{k_B T} \right)}. \quad \text{---- [12]}$$

Thus, the above equation is the expression for the density of electrons in the conduction band for an intrinsic semiconductor.

### 10.5.2 Expression for density of holes in the valence band

The density of holes  $n_h$  in the valence band can be evaluated by integrating the product of density of states  $Z(E) dE$  and the probability function for a hole  $[1-f(E)]$  between the limits from the bottom of the valence band labelled  $(-\infty)$  to the top of the valence band labelled  $E_v$  as shown in figure 10.2.

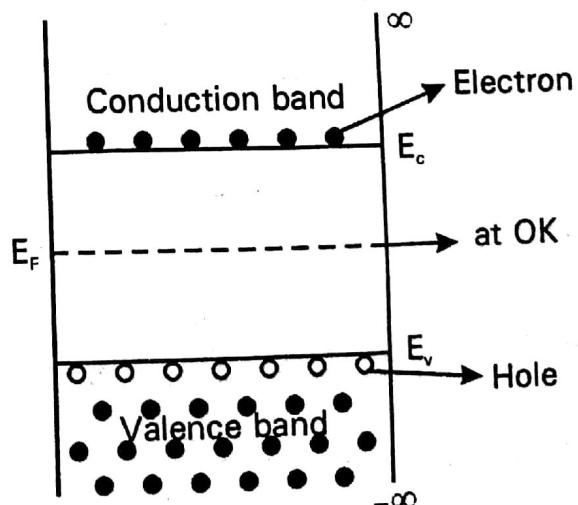


Figure 10.2 : Energy band diagram for an intrinsic semiconductor at  $T > 0K$

∴ The density of holes in the valence band is

$$n_h = \int_{-\infty}^{E_v} Z(E)dE [1 - f(E)] \quad \text{--- [13]}$$

[Here, the limits are from  $-\infty$  to  $E_v$  for the reasons similar to the one's stated in the evaluation of  $n_e$ .]

- Note :**
- **Probability function for a hole :** As per the rules of probability, the probability of absence = 1 – probability of presence. Hence, based on above rule, the absence of an electron at some energy level means, the presence of a hole in the same energy level in the band.
  - ∴ Hole probability = 1 – electron probability. We know the electron probability is  $f(E)$ .
  - ∴ The probability that a hole is available with energy  $E$  is  $= 1 - f(E)$ .

$$\begin{aligned} \therefore 1 - f(E) &= \left[ 1 - \frac{1}{1 + e^{\left(\frac{E-E_F}{k_B T}\right)}} \right] \\ &= 1 - \left[ 1 + e^{\left(\frac{E-E_F}{k_B T}\right)} \right]^{-1} \end{aligned}$$

Using binomial series  $(1+x)^{-1} = 1 - x + x^2 - x^3 + \dots$  with  $x = e^{\left(\frac{E-E_F}{k_B T}\right)}$  and neglecting higher powers, we get

$$1 - f(E) = 1 - \left[ 1 - e^{\left(\frac{E-E_F}{k_B T}\right)} \right] = - \left[ -e^{\left(\frac{E-E_F}{k_B T}\right)} \right]$$

$$\text{or } 1 - f(E) = e^{\left(\frac{E-E_F}{k_B T}\right)}. \quad \text{--- [14]}$$

From the above equation it is clear that, in valence band  $E < E_F$ , i.e., the fermi level  $E_F$  is again assumed to lie a few  $k_B T$  above  $E_v$ . Therefore, the function  $[1 - f(E)]$  decreases exponentially. Also, it implies that holes reside near the top of the valence band.

The expression for  $Z(E)dE$  for holes behaving as a free particle with effective mass  $m_h^*$  is given by, [with reference to equation (3)].

$$Z(E)dE = \frac{\pi}{2} \left( \frac{8m_h^*}{h^2} \right)^{3/2} (E_v - E)^{1/2} dE \quad \text{--- [15]}$$

**Note :** • Since, the energy for the hole increases in the downward direction in the band structure, E has been replaced by  $E_v - E$  in the expression of  $Z(E)dE$ .

Therefore, substituting equation (14) and (15) in equation (13), we get

$$n_h = \frac{\pi}{2} \left( \frac{8m_h^*}{h^2} \right)^{3/2} \int_{-\infty}^{E_v} (E_v - E)^{1/2} e^{\left( \frac{E-E_F}{k_B T} \right)} dE \quad \text{--- [16]}$$

To solve the above integration, let us define

$$E_v - E = x k_B T \quad \text{--- [17]}$$

$$\therefore E = E_v - x k_B T \quad \text{--- [18]}$$

On differentiating the above equation, we get

$$dE = -dx k_B T \quad \text{--- [19]}$$

Based on equation (17), the integral limits for equation (16) also get changed accordingly as follows.

$$\text{When } E = \infty$$

$$E_v + \infty = x$$

$$\text{or } x = \infty$$

(Lower limit)

$$\text{Similarly, when } E = E_v$$

$$0 = x$$

$$\text{or } x = 0$$

(Upper limit)

Hence, on substituting equations (17), (18), (19) and the corresponding limits in equation (16), we get

$$n_h = \frac{\pi}{2} \left( \frac{8m_h^*}{h^2} \right)^{3/2} \int_{\infty}^0 (x k_B T)^{1/2} e^{\left[ \frac{E_v - x k_B T - E_F}{k_B T} \right]} (-dx k_B T)$$

On simplifying,

$$n_h = \frac{\pi}{2} \left( \frac{8m_h^*}{h^2} \right)^{3/2} (k_B T)^{1/2} (k_B T)^1 e^{\left( \frac{E_v - E_F}{k_B T} \right)} \int_{\infty}^0 x^{1/2} e^{-x} (-dx k_B T)$$

$$\text{or } n_h = \frac{\pi}{2} \left( \frac{8m_h^* k_B T}{h^2} \right)^{3/2} e^{\left( \frac{E_v - E_F}{k_B T} \right)} \int_0^{\infty} x^{1/2} e^{-x} dx \quad \text{--- [20]}$$

Since,  $\int_0^{\infty} x^{1/2} e^{-x} dx = \frac{\sqrt{\pi}}{2}$ , equation (20) becomes,

$$n_h = \frac{\pi}{2} \left( \frac{8m_h^* k_B T}{h^2} \right)^{3/2} e^{\left( \frac{E_v - E_F}{k_B T} \right)} \frac{\sqrt{\pi}}{2}$$

$$n_h = \frac{1}{4} \left( \frac{8\pi m_h^* k_B T}{h^2} \right)^{3/2} e^{\left( \frac{E_v - E_F}{k_B T} \right)}$$

$$\text{or } n_h = 2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{3/2} e^{\left( \frac{E_v - E_F}{k_B T} \right)} \quad \text{--- [2]}$$

Thus, the above equation is the expression for the density of holes in the valence band for an intrinsic semiconductor.

## 10.6 Fermi Level and its Variation with Temperature

We know in an intrinsic semiconductor

$$n_e = n_h$$

i.e., {Density of electrons in the conduction band} = {Density of holes in the valence band}

Therefore, [from equation (12) and (21)]

$$2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2} e^{\left( \frac{E_F - E_c}{k_B T} \right)} = 2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{3/2} e^{\left( \frac{E_v - E_F}{k_B T} \right)}$$

$$\text{or } (m_e^*)^{3/2} e^{\left( \frac{E_F - E_c}{k_B T} \right)} = (m_h^*)^{3/2} e^{\left( \frac{E_v - E_F}{k_B T} \right)}$$

Rearranging the above equation,

$$e^{\left( \frac{2E_F}{k_B T} \right)} = \left( \frac{m_h^*}{m_e^*} \right)^{3/2} e^{\left( \frac{E_v + E_c}{k_B T} \right)} \quad \text{--- [1]}$$

Taking logarithm on both sides,

$$\frac{2E_F}{k_B T} = \frac{3}{2} \ln \left( \frac{m_h^*}{m_e^*} \right) + \frac{E_v + E_c}{k_B T}$$

[The RHS of equation (1) has been written using the formula  $\ln(ab) = \ln a + \ln b$

**Note :** •  $\ln$  is natural base of logarithm  $\ln N = \log_e N = 2.302 \log_{10} N$ .

$$\therefore E_F = \frac{3k_B T}{4} \ln \left( \frac{m_h^*}{m_e^*} \right) + \frac{E_v + E_c}{2} \quad \text{--- [2]}$$

when  $m_e^* = m_h^*$ , the above equation gets reduced to

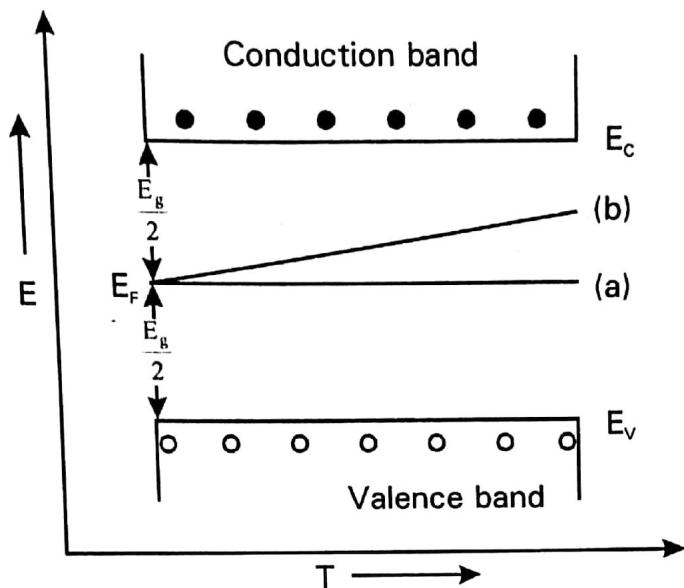
$$E_F = \frac{E_v + E_c}{2}, \text{ Since } \ln(1) = 0 \quad \text{--- [3]}$$

Thus, the fermi level is in the middle of the band gap. i.e.,  $E_F = \frac{E_g}{2}$ . ----- [4]

As shown in figure 10.3a  $E_g$  lies half way between the top of valence band and bottom of conduction band.

### Dependence of $E_F$ on temperature

The variation of fermi level with temperature for an intrinsic semiconductor is shown in figure 10.3. At  $T = 0K$ , the fermi level lies exactly in the middle of forbidden gap as shown in figure 10.3a.



**Figure 10.3 : Position of fermilevel in an intrinsic semiconductor at various temperatures**

At low temperature region,  $E_F$  is practically independent of temperature. But, there is a slight variation in  $E_F$  in the high temperature region. The reason is, in actual case  $m_e^* > m_h^*$ . Thus, the

term  $\ln\left(\frac{m_h^*}{m_e^*}\right)$  begins to contribute slightly. This results in a small increase in the magnitude of  $E_F$ .

Thus the fermi level gets raised slightly as shown in figure 10.3b as  $T$  increases.

### 10.7 Law of Mass Action for Semiconductors

*The law states that, for a given semiconductor material either intrinsic or extrinsic, the product of charge carrier concentration remains a constant at any given temperature even if the doping is varied.*

$$\text{i.e., } n_e \cdot n_h = n_i^2 = \text{a constant}$$

----- [1]

where  $n_i$  is the intrinsic carrier concentration or also called as intrinsic charge carrier density.

Based on law of mass action,

$$n_i^2 = n_e \cdot n_h = 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{3/2} e^{\left(\frac{E_F - E_c}{k_B T}\right)} \times 2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{3/2} e^{\left(\frac{E_v - E_F}{k_B T}\right)}$$

$$\text{or } n_i^2 = 2^2 \left( \frac{2\pi k_B T}{h^2} \right)^3 \left( m_e^* m_h^* \right)^{3/2} e^{\left( \frac{E_v - E_c}{k_B T} \right)}$$

$$\therefore n_i = 2 \left( \frac{2\pi k_B T}{h^2} \right)^{3/2} \left( m_e^* m_h^* \right)^{3/4} e^{\left( \frac{E_v - E_c}{2k_B T} \right)} \quad \text{--- [2]}$$

$$\text{or } n_i = 2 \left( \frac{2\pi k_B T}{h^2} \right)^{3/2} \left( m_e^* m_h^* \right)^{3/4} e^{\left( \frac{-E_g}{2k_B T} \right)} \quad [\text{Since } E_c - E_v = E_g].$$

The above equation shows that, the product of  $n_e \cdot n_h$  does not depend on  $E_F$ , but remains a constant at a given temperature. Thus, equation (2) gives the intrinsic carrier concentration.

For an intrinsic semiconductor

$$n_e = n_h = n_i.$$

#### 10.8 Mobility and Conductivity

# EXTRINSIC SEMICONDUCTORS

## 11.1 Introduction

*Extrinsic semiconductor is an impure semiconductor formed from an intrinsic semiconductor by adding a small quantity of impurity atoms also called dopants.*

*The process of adding impurities to the semiconductor crystal is known as doping.*

Addition of impurity alters the electrical properties of the semiconductor and improves its conductivity. The conductivity of an extrinsic semiconductor depends primarily on the number of dopant atoms. The purpose of doping is to produce an enormous amount of charge carriers in the semiconductors.

Based on the element of doping, the extrinsic semiconductors are of two types,

- (i) n-type semiconductor
- (ii) p-type semiconductor.



## 11.2 n-type Semiconductor

A n-type semiconductor gets formed on doping atoms that have five valence electrons to an intrinsic semiconductor like Si or Ge.

Consider the intrinsic semiconductor Si which has 4 valence electrons. Each of the four valence electron is covalently bonded with one of the four adjacent Si atoms as shown in figure 11.1.

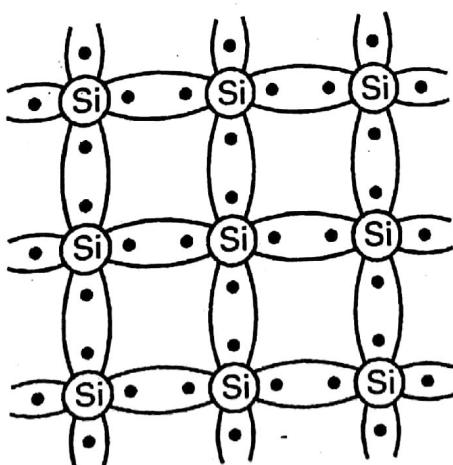
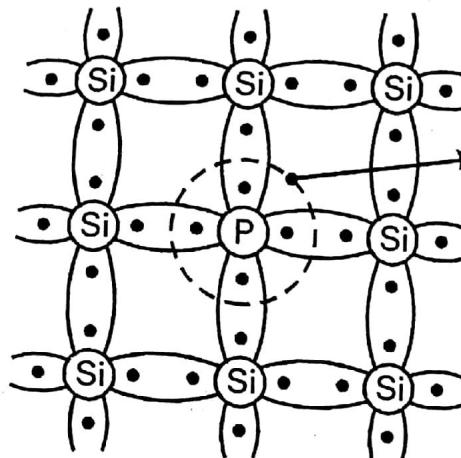
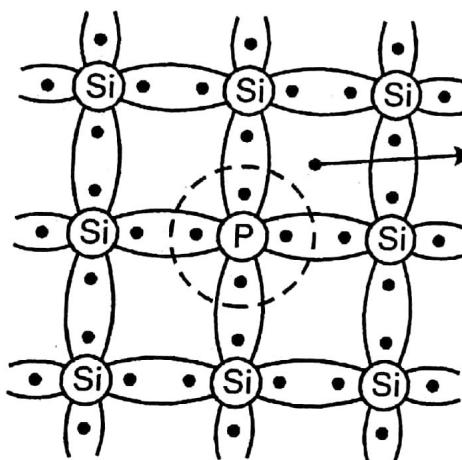
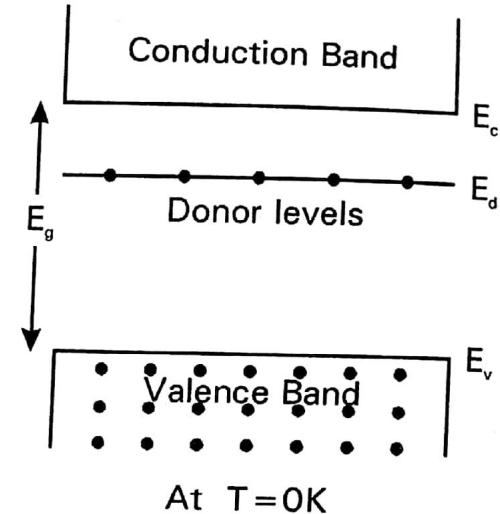


Figure 11.1

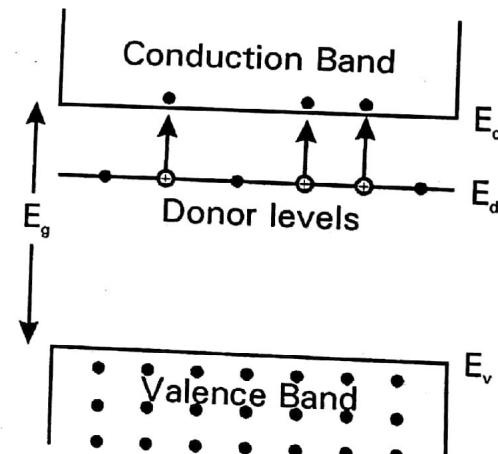
To this Si atom, if an atom with five valence electrons such as Phosphorus (P), Arsenic ( $As$ ) or Antimony (Sb) is incorporated into the crystal then, four of the electrons from the dopant atom will participate in the covalent bond formation there by leaving an extra electron (fifth electron) in the unbonded state as shown in figure 11.2.



At  $T = 0K$



At  $T > 0K$



At  $T > 0K$

**Figure 11.2 : Charge carrier excitation in a n-type semiconductor**

This extra electron is only weakly bound to the atom and enters into an energy level in a donor state just below the conduction band as shown in the figure.

Since this extra electron is not tightly bound to the atom, all such electrons at room temperature can get excited to the conduction band even for a small increase in the external energy leaving the parent atom positively ionised.

Since the pentavalent atoms donates electrons to the conduction band in obtaining n-type semiconductor they are also called as donor atoms.

$E_d$  is the minimum energy required for the electron to enter the conduction band.

- Note :**
- **Donor energy level :** It is the localised electronic states or levels introduced by the donor atoms because of the presence of an extra electron.
  - **$E_d$  :** Donor energy is defined as the energy difference between the bottom of the conduction band and the donor energy level.

Since excitation of these weakly bound electrons does not result in the formation of a hole, the number of electrons in such a material far exceeds the number of thermally generated holes. Hence, in this type of semiconductors electrons are the majority carriers and the holes are the minority carriers.

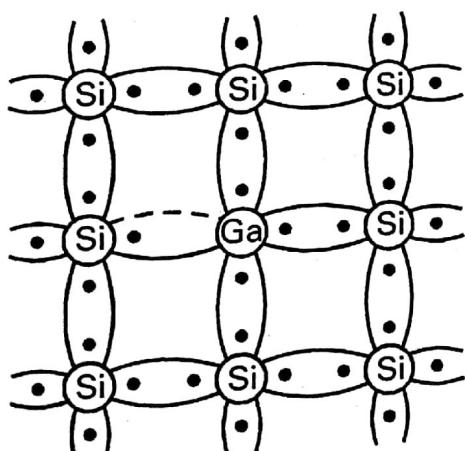
In case, if the thermal energy is sufficiently high, in addition to the ionisation of donor impurity atoms breaking of covalent bond may also occur thereby giving rise to generation of electron hole pairs.

### 11.3 p-type Semiconductor

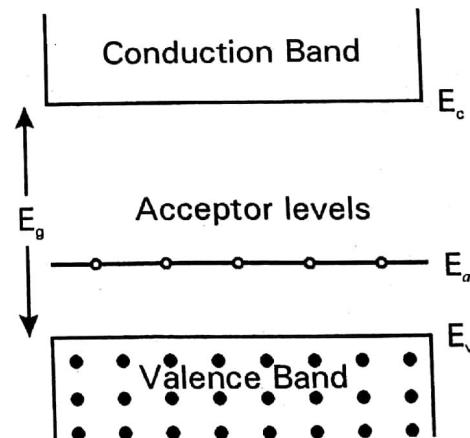
A p-type semiconductor gets formed on doping atoms that have three valence electrons to an intrinsic semiconductor like Si or Ge.

The trivalent elements like Gallium (Ga), Indium (In) or Boron (B) can be added as a dopant to an intrinsic semiconductor.

Let us assume a trivalent element Ga is added to an intrinsic semiconductor Si. All the three valence electrons of Ga will form three covalent bonds with three neighbouring Si atoms as shown in figure 11.3.

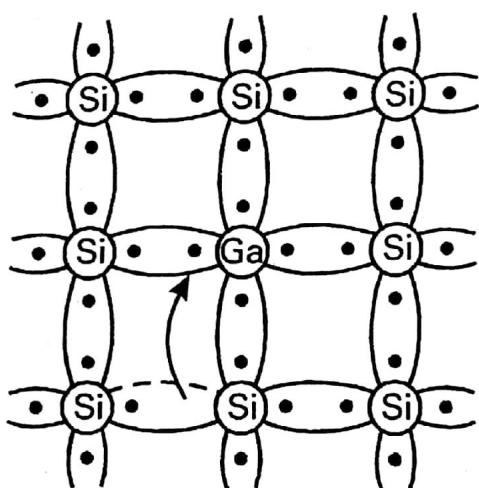
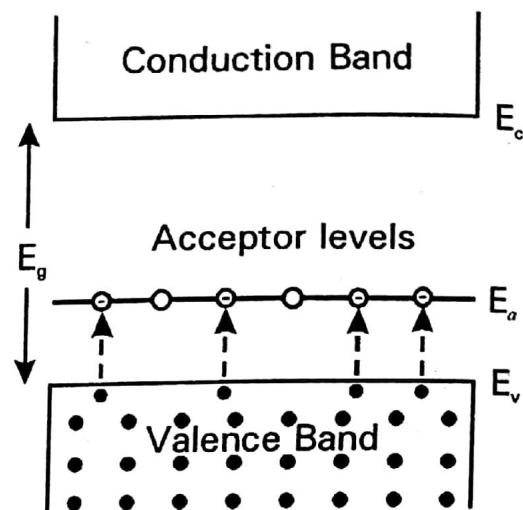


(a) At  $T = 0\text{K}$



(a) At  $T = 0\text{K}$

**Figure 11.3 : Charge carrier excitation in a p-type semiconductor**

(a) At  $T > 0\text{K}$ (b) At  $T > 0\text{K}$ **Figure 11.3 : Charge carrier excitation in a p-type semiconductor**

Thus, the dopant is in need of an extra electron to complete its fourth covalent bond formation with Si.

This extra electron may be supplied by Si, thereby creating an electron hole (i.e., a vacant site) in the valence band that can be filled by electrons from the other locations in the band in turn creating another vacant site. Thus, the holes act as acceptors of electrons. These hole sites have an energy slightly higher than the normal energy and create an energy level called acceptor energy level which lie just above the valence band.

*Since the dopant atoms Ga accepts electrons they are also called as acceptors.*

An electron must gain energy of the order  $E_a$  in order to create a hole in the valence band. Thus, these acceptor atoms get negatively ionised after accepting the electrons from the valence band even at room temperature. Hence, holes are created in the valence band and are ready for conduction.

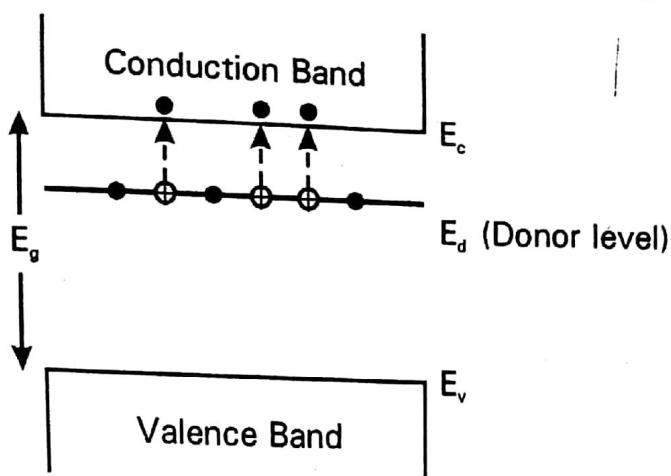
When a sufficiently large number of acceptor atoms are added, the holes greatly outnumber the thermally excited electrons. Hence, the holes are the majority carriers while electrons are the minority carriers in p-type semiconductor.

In case, if the temperature is sufficiently high, in addition to the above process, additional electron hole pairs also get generated due to breaking of covalent bonds.

#### 11.4 Expression for Carrier Concentration in n-type Semiconductor

As a first step, before obtaining an expression for the carrier concentration of electrons in the conduction band of an extrinsic n-type semiconductor, let us derive an expression for the fermilevel.

The energy level diagram for a n-type semiconductor is shown in figure 11.4.



**Figure 11.4 : Charge carrier excitation in a n-type semiconductor**

Let \$N\_d\$ be the donor concentration i.e., the number of donor atoms per unit volume of the material and \$E\_d\$ is the donor energy level in a n-type semiconductor.

**Note :** • \$N\_d\$ can also be taken as the donor energy level per unit volume of energy \$E\_d\$.  
i.e., \$N\_d\$ is the density of donor energy level.

Let us assume that \$E\_c - E\_F > k\_B T\$. Then, in that case, density of electrons in the conduction band is given as

$$n_e = 2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{\frac{3}{2}} e^{\left( \frac{E_F - E_c}{k_B T} \right)} \quad \text{---- [1]}$$

At 0K, the fermi level \$E\_F\$ lies between \$E\_c\$ and \$E\_d\$. Also, at very low temperature, all donor levels will be filled with electrons (donor atoms). With increase of temperature, more and more donor atoms get positively ionised due to electron donation to the conduction band and hence, the density of electrons in the conduction band increases.

If we assume that \$E\_F\$ lies more than a few \$k\_B T\$ above the donor level \$E\_d\$; then, the density of ionised donor atoms \$N\_d^+\$ must be equal to the product of density of the donor atoms \$N\_d\$ and the probability function \$[1 - f(E\_d)]\$ for an electron absence in the donor energy level.

$$\text{i.e., } N_d^+ = N_d [1 - f(E_d)] \quad \text{---- [2]}$$

### Solving for \$[1 - f(E\_d)]\$

$$\text{We know } f(E_d) = \frac{1}{1 + e^{\left( \frac{E_d - E_F}{k_B T} \right)}}$$

\* Compare this simplification with that of section 10.5.2.

$$\therefore 1 - f(E_d) = 1 - \frac{1}{1 + e^{\left( \frac{E_d - E_F}{k_B T} \right)}} = 1 - \left[ 1 + e^{\left( \frac{E_d - E_F}{k_B T} \right)} \right]^{-1}$$

$$= 1 - \left[ 1 - e^{\left( \frac{E_d - E_F}{k_B T} \right)} \right]$$

$$\text{Hence, } 1 - f(E_d) = e^{\left( \frac{E_d - E_F}{k_B T} \right)}$$

[3]

From the above equation it is clear that  $E_d < E_F$  i.e.,  $E_d - E_F$  is negative.

$$\text{Hence, substituting equation (3) in equation (2), we get } N_d^+ = N_d e^{\left( \frac{E_d - E_F}{k_B T} \right)}$$

[4]

At very low temperature, since no electron hole pair is generated due to breaking of covalent bonds, the density of electrons  $n_e$  in the conduction band must be equal to the density of positively ionised donor atoms  $N_d^+$ .

$$\text{i.e., } n_e = N_d^+$$

$$\therefore 2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{\frac{3}{2}} e^{\left( \frac{E_F - E_c}{k_B T} \right)} = N_d e^{\left( \frac{E_d - E_F}{k_B T} \right)}$$

Taking logarithm on both sides we get,

$$\ln \left[ 2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{\frac{3}{2}} \right] + \frac{E_F - E_c}{k_B T} = \ln N_d + \frac{E_d - E_F}{k_B T}$$

On rearranging the above equation we get,

$$\frac{E_F - E_c}{k_B T} - \left( \frac{E_d - E_F}{k_B T} \right) = \ln N_d - \ln \left[ 2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{\frac{3}{2}} \right]$$

Multiplying on both sides with  $k_B T$  and after simplification the above equation becomes,

$$2E_F - (E_d + E_c) = k_B T \ln \left( \frac{N_d}{2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{\frac{3}{2}}} \right) \quad [\text{using } \ln a - \ln b = \ln \left( \frac{a}{b} \right)]$$

$$\therefore 2E_F = (E_d + E_c) + k_B T \ln \left( \frac{N_d}{2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{\frac{3}{2}}} \right)$$

$$\text{or } E_F = \frac{(E_d + E_c)}{2} + \frac{k_B T}{2} \ln \left( \frac{\frac{N_d}{2} \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{\frac{3}{2}}}{2} \right) \quad \dots [5]$$

At  $T = 0K$ , using the above equation we get,

$$E_F = \frac{E_d + E_c}{2}. \quad \dots [6]$$

Thus, equation (6) implies that, the fermilevel  $E_F$  lies exactly at the middle of the donor level  $E_d$  and the bottom of the conduction band  $E_c$  as shown in figure 11.5.

#### 11.4.1 Expression for Carrier Concentration (Density) of Electrons in the Conduction Band

From equation (1), the density of electrons in the conduction band is given by

$$n_e = 2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{\frac{3}{2}} e^{\left( \frac{E_F - E_c}{k_B T} \right)}$$

Substituting for  $E_F$  from equation (5) in the above equation, we get an expression for the density of electrons in the conduction band.

Let us first simplify the term  $E_F - E_c$  in  $e^{\left( \frac{E_F - E_c}{k_B T} \right)}$  factor.

$$E_F - E_c = \frac{E_d + E_c}{2} + \frac{k_B T}{2} \ln \left( \frac{\frac{N_d}{2} \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{\frac{3}{2}}}{2} \right) - E_c$$

$$E_F - E_c = \frac{E_d - E_c}{2} + \frac{k_B T}{2} \ln \left( \frac{\frac{N_d}{2} \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{\frac{3}{2}}}{2} \right)$$

On dividing the above equation by  $k_B T$ , we get

$$\frac{E_F - E_c}{k_B T} = \frac{E_d - E_c}{2k_B T} + \frac{1}{2} \ln \left( \frac{N_d}{2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{\frac{3}{2}}} \right)$$

or  $\frac{E_F - E_c}{k_B T} = \frac{E_d - E_c}{2k_B T} + \ln \left( \frac{N_d^{\frac{1}{2}}}{\left[ 2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{\frac{3}{2}} \right]^{\frac{1}{2}}} \right) \quad \text{---- [7]}$

[Using  $x \ln \left( \frac{a}{b} \right) = \ln \frac{a^x}{b^x}$ ]

Therefore, substituting equation (7) in the expression for  $n_e$ , we get

$$n_e = \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{\frac{3}{2}} \exp \left[ \left( \frac{E_d - E_c}{2k_B T} \right) + \ln \frac{N_d^{\frac{1}{2}}}{\left[ 2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{\frac{3}{2}} \right]^{\frac{1}{2}}} \right]$$

Simplifying the exponential term using the formula

$$e^{a+b} = e^a \cdot e^b, \text{ we get}$$

$$n_e = 2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{\frac{3}{2}} e^{\left( \frac{E_d - E_c}{2k_B T} \right)} \frac{N_d^{\frac{1}{2}}}{\left[ 2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{\frac{3}{2}} \right]^{\frac{1}{2}}}$$

On simplification, we get

$$n_e = (2 N_d)^{1/2} \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/4} e^{\left( \frac{E_d - E_c}{2k_B T} \right)}. \quad \text{--- [8]}$$

Hence, the density of electrons in the conduction band is proportional to the square root of donor concentration  $N_d$ .

This equation holds good only at low temperatures and at high temperatures, the intrinsic carrier concentration must also be taken into account. Thus, at very high temperatures, the n-type semiconductor behaves like an intrinsic semiconductor.

The ionisation energy of donors is given by  $\Delta E = E_c - E_d$ . It is the amount of energy required to transfer an electron from the donor energy level  $E_d$  to the conduction band.

### Electrical conductivity

For a pure n-type semiconductor which has only the donor atoms, the electrical conductivity is given by  $\sigma = n_e e \mu_e$ , where  $n_e$  is given by equation (8) and  $\mu_e$  is the mobility of electrons.

## 11.5 Variation of Fermi Level with Temperature and Impurity Concentration

### $E_F$ Variation with temperature

The fermi level increases with increase of temperature as given by equation (5). As the temperature gets slowly increased more and more donor atoms get ionised due to transfer of electrons to the conduction band, and the fermi level  $E_F$  lies in between  $E_c$  and  $E_d$ .

At a particular temperature, all the donor atoms would have been ionised. Hence, beyond this temperature electron hole pairs get generated due to breaking of covalent bonds; and, the material tends to behave as an intrinsic semiconductor. Thus, the fermi level gradually shifts towards the intrinsic fermi level  $E_i$  as shown in figure 11.5.

### $E_F$ variation with donor concentration

In the figure 11.5 the variation of fermi level  $E_F$  with high and low donor concentration is indicated.

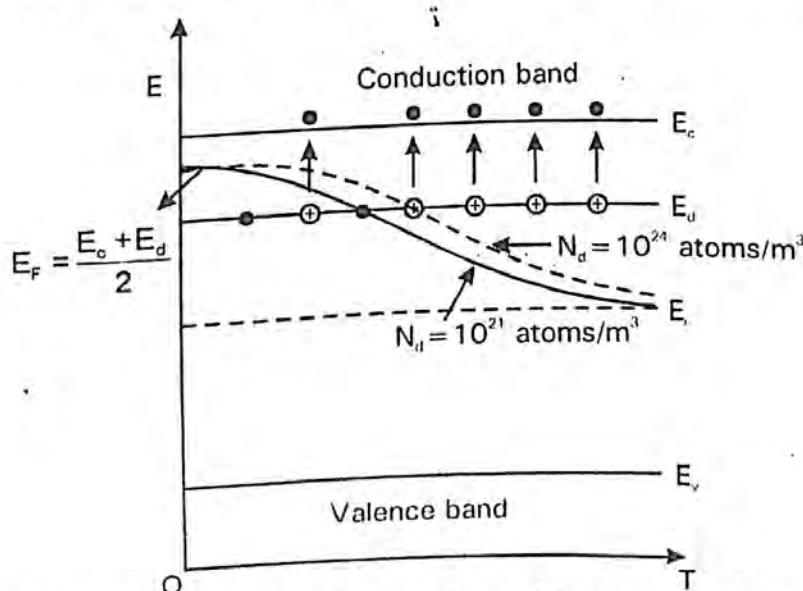


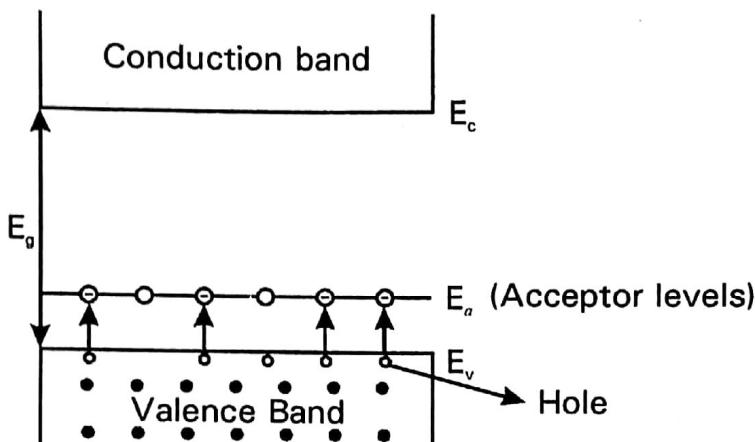
Figure 11.5 : Variation of fermilevel position with temperature and carrier concentration

It is seen from the figure; that, the shifting of fermi level with rise of temperature is slow in the case of higher donor concentration than, the lower donor concentration. Naturally, highly doped semiconductor will lose their extrinsic behaviour only at a very high temperature application.

### 11.6 Expression for Carrier Concentration in p-type Semiconductor

As a first step, before obtaining an expression for the carrier concentration of holes in the valence band of an extrinsic p-type semiconductor let us derive an expression for the fermi level.

The energy level diagram for a p-type semiconductor is shown in figure 11.6.



**Figure 11.6 : Charge carrier excitation in a p-type semiconductor**

Let  $N_a$  be the acceptor concentration i.e., the number of acceptor atoms per unit volume in a p-type semiconductor and  $E_a$  is the acceptor energy level.

**Note :** •  $N_a$  can also be taken as the acceptor energy level per unit volume of energy  $E_a$ .  
i.e.,  $N_a$  is density of acceptor energy level.

Let us assume that  $E_a - E_F > k_B T$ . Then, in that case, density of holes in the valence band is given as

$$n_h = 2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{\frac{3}{2}} e^{\left( \frac{E_v - E_F}{k_B T} \right)} \quad \text{--- [1]}$$

At 0K, the fermi level  $E_F$  lie between  $E_v$  and  $E_a$ . Also, at very low temperature, all acceptor levels remain empty. With increase of temperature, more and more acceptor atoms get negatively ionised due to electron's transfer from the valence band to the acceptor energy level  $E_a$ . Hence, the density of holes in the valence band increases.

If we assume that  $E_F$  lies below the acceptor energy level  $E_a$  then, the density of negatively ionised acceptor atoms  $N_a^-$  must be equal to the product of density of acceptor atoms  $N_a$  and the probability function  $f(E_a)$  for the occupancy of an electron.

$$\text{i.e., } N_a^- = N_a f(E_a) \quad \text{--- [2]}$$

we know  $f(E_a) = \frac{1}{1 + e^{\left(\frac{E_a - E_F}{k_B T}\right)}}$  ----- [3]

Since, the acceptor level lies above the fermi level,  $E_a - E_F$  is positive. Therefore, the term 1 in the denominator of equation (3) can be neglected, compared to  $e^{\left(\frac{E_a - E_F}{k_B T}\right)}$  which is very large.

Hence, equation (3) can be written as,

$$f(E_a) = e^{\left(\frac{E_F - E_a}{k_B T}\right)} \quad \text{----- [4]}$$

Therefore, substituting equation (4) in equation (2), we get

$$N_a^- = N_a e^{\left(\frac{E_F - E_a}{k_B T}\right)} \quad \text{----- [5]}$$

At very low temperature, the density of holes  $n_h$  in the valence band must be equal to the density of negatively ionised acceptor atoms  $N_a^-$ .

i.e.,  $n_h = N_a^-$

$$\therefore 2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{\frac{3}{2}} e^{\left(\frac{E_v - E_F}{k_B T}\right)} = N_a e^{\left(\frac{E_F - E_a}{k_B T}\right)}$$

Taking logarithm on both sides, we get

$$\ln \left[ 2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{\frac{3}{2}} \right] + \frac{E_v - E_F}{k_B T} = \ln N_a + \frac{E_F - E_a}{k_B T}$$

Rearranging the above equation,

$$\frac{E_v - E_F}{k_B T} - \left( \frac{E_F - E_a}{k_B T} \right) = \ln N_a - \ln \left[ 2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{\frac{3}{2}} \right]$$

$$\frac{-2E_F}{k_B T} + \frac{E_v + E_a}{k_B T} = \ln \left[ \frac{N_a}{2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{\frac{3}{2}}} \right]$$

(On multiplying with -ve sign on both sides and rearranging)

$$\frac{2E_F}{k_B T} = \frac{E_v + E_a}{k_B T} - \ln \left[ \frac{N_a}{2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{\frac{3}{2}}} \right]$$

Hence,  $E_F = \frac{E_v + E_a}{2} - \frac{k_B T}{2} \ln \frac{N_a}{2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{\frac{3}{2}}}$  ---- [6]

At  $T = 0K$ , using the above equation, we get

$$E_F = \frac{E_v + E_a}{2}$$
 ---- [7]

This equation (7) implies that, the fermi level  $E_F$  lies exactly at the middle of the acceptor level  $E_a$  and the top of the valence band  $E_v$  as shown in figure 11.7.

### 11.6.1 Expression for Carrier Concentration (Density) of Holes in the Valence Band

From equation (1), the density of holes in the valence band is given by,

$$n_h = 2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{\frac{3}{2}} e^{\left( \frac{E_v - E_F}{k_B T} \right)}$$

Substituting for  $E_F$  from equation (6) in the above equation, we get an expression for the density of holes in the valence band.

Let us first simplify the term  $E_v - E_F$  in  $e^{\left( \frac{E_v - E_F}{k_B T} \right)}$  factor.

$$E_v - E_F = E_v - \frac{(E_v + E_a)}{2} + \frac{k_B T}{2} \ln \frac{N_a}{2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{\frac{3}{2}}}$$

$$= \frac{E_v - E_a}{2} + \frac{k_B T}{2} \ln \frac{N_a}{2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{\frac{3}{2}}}$$

On dividing by  $k_B T$ , we get

$$\frac{E_v - E_F}{k_B T} = \frac{E_v - E_a}{2k_B T} + \frac{1}{2} \ln \frac{N_a}{2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{3/2}}$$

or  $\frac{E_v - E_F}{k_B T} = \frac{E_v - E_a}{2k_B T} + \ln \frac{N_a^{1/2}}{\left[ 2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{3/2} \right]^{1/2}}$  ---- [8]

Therefore, substituting equation (8) in the expression for  $n_h$ , we get

$$n_h = 2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{3/2} \exp \left[ \left( \frac{E_v - E_a}{2k_B T} \right) + \ln \frac{N_a^{1/2}}{\left[ 2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{3/2} \right]^{1/2}} \right]$$

Simplifying the exponential term using the formula  $e^{a+b} = e^a \cdot e^b$ , we get

$$= 2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{3/2} e^{\left( \frac{E_v - E_a}{2k_B T} \right)} \frac{N_a^{1/2}}{\left[ 2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{3/2} \right]^{1/2}}$$

Hence, after simplification,

$$n_h = (2N_a)^{1/2} \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{3/4} e^{\left( \frac{E_v - E_a}{2k_B T} \right)}. \quad \text{---- [9]}$$

From equation (9), it is observed that, the density of holes in the valence band is proportional to the square root of acceptor concentration  $N_a$ .

Just similar to n-type semiconductor, at very high temperature, the p-type semiconductor behaves like an intrinsic semiconductor.

The ionisation energy of acceptors is given by  $\Delta E = E_a - E_v$ . It is the energy required for an electron to move from valence band  $E_v$  to the acceptor energy level  $E_a$ .

### Electrical conductivity

For a pure p-type semiconductor, which has only the acceptor atoms, the electrical conductivity is given by

$$\sigma = n_h e \mu_h, \text{ where } n_h \text{ is given by equation (9) and } \mu_h \text{ is the hole mobility.}$$

### 11.7 Variation of Fermi Level with Temperature and Impurity Concentration

#### $E_F$ variation with temperature

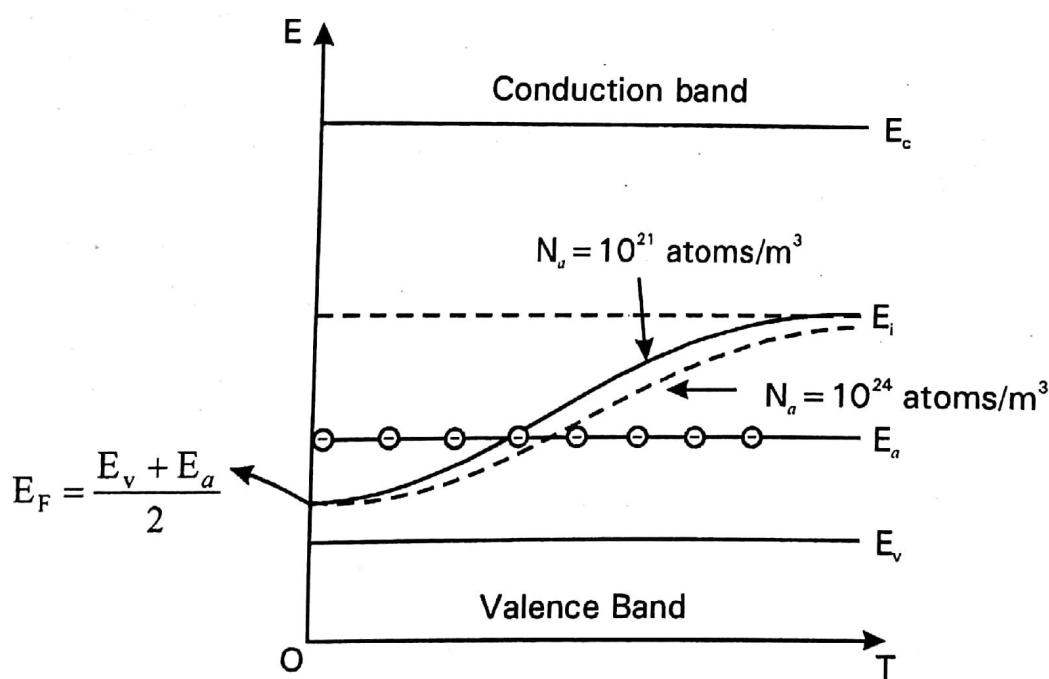
The fermi level decreases with increase of temperature as given by equation (6). As the temperature gets slowly increased more and more acceptor atoms get negatively ionised due to transfer of electrons from the valence band and the fermi level  $E_F$  lies in between  $E_v$  and  $E_a$ .

But, at a particular temperature, all the acceptor atoms would have been ionised. Hence, beyond this temperature electron hole pairs get generated due to breaking of covalent bonds; and, the material tends to behave as an intrinsic semiconductor. Thus, the fermi level gradually shifts towards the intrinsic fermi level  $E_i$  as shown in figure 11.7.

#### $E_F$ variation with acceptor concentration

In figure 11.7 the variation of fermi level  $E_F$  with high and low acceptor concentration is indicated.

It is seen from the figure; that, the shifting of fermi level with rise of temperature is slow in the case of highly doped semiconductor. The reason is, highly doped semiconductors will lose their extrinsic behaviour only at a very high temperature application.

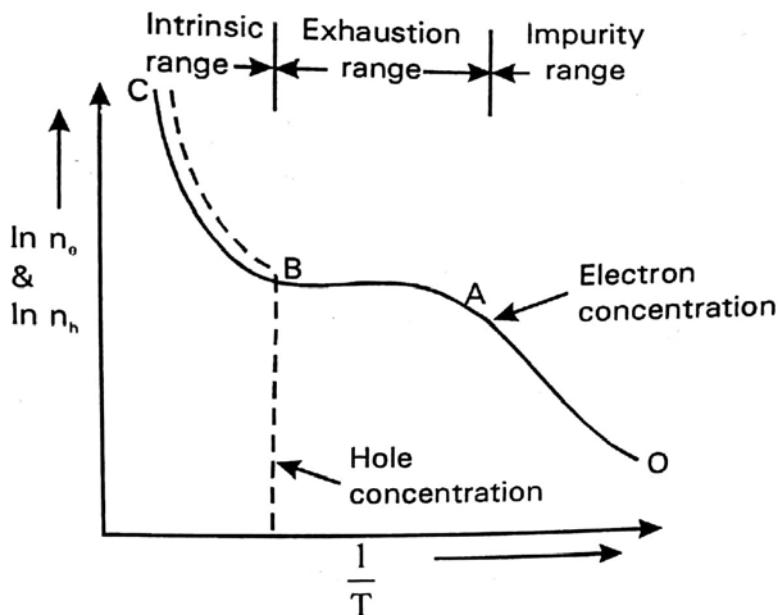


Figurere 11.7 : Variation of fermi level position with temperature and carrier concentration

### 11.8 Variation of Carrier Concentration with Temperature

The variation of carrier concentration with temperature for a n-type semiconductor is shown in figure 11.8.

In a n-type semiconductor electrons are the majority carriers and holes are the minority carriers.



*Figure 11.8 : Variation of carrier concentration with temperature*

At 0K both the conduction band and valence band are free from any charge carriers and hence conductivity is zero.

Now, when the temperature is slowly increased, the donor atoms get ionised and hence, the electron concentration in conduction band increases as shown by the region OA in figure 11.8. Since this range occurs due to impurity atoms ionisation this region OA is called impurity range. During this process, the fermi level shifts towards the donor level  $E_d$  from the middle of  $E_c$  and  $E_d$ .

With the slow increase of temperature more and more donor atoms get ionised. Hence, at about room temperature all the donor atoms would have been ionised and so, the concentrations of electrons in the conduction band remains constant over a certain range of temperature as shown by AB region in the curve. This range is called the exhaustion range and in this range the fermi level crosses the donor level  $E_d$ .

As the temperature is increased further, and if the thermal energy is sufficiently high, the covalent bonds get broken and thus electron-hole pairs get generated. As a result, electrons from the valence band starts moving towards the conduction band and thereby increasing the electron concentration in the conduction band considerably. Thus, with continuous increase of temperature, the electrons from the valence band completely out number the donor electrons.

During this process, the fermi levels also moves down gradually until it reaches the middle of the forbidden gap. Thus, the material becomes completely intrinsic in the range BC, and is known as intrinsic range.

### Hole concentration

The dotted curve indicates the hole concentration. In the intrinsic range both the hole and electron concentration curve overlap since they become equal in number. The exhaustion region is observable only for smaller concentration of  $N_d$ . If  $N_d$  is large, the low temperature impurity region passes to intrinsic region without passing the flat region AB.

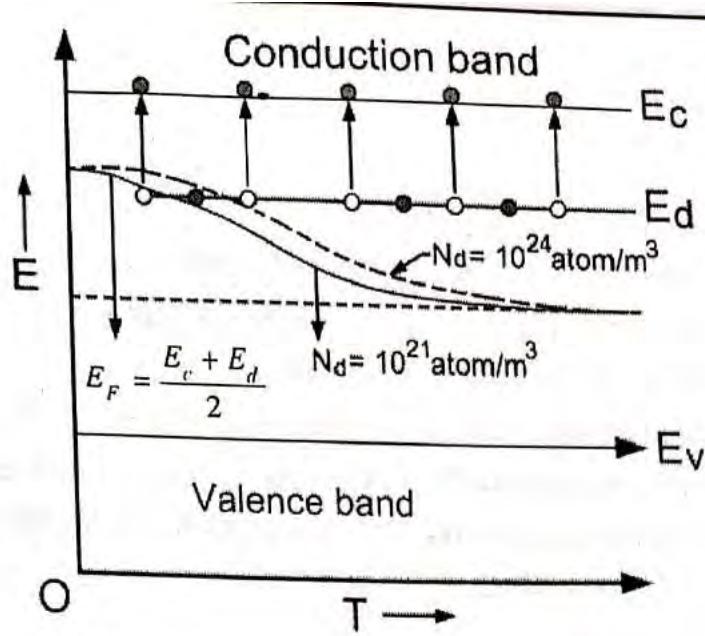
**Note :** • The variation of carrier concentration with temperature in a p-type semiconductor can also be explained in the same manner.

### 2.3.5.2 Variation of Fermi level with temperature and Impurity concentration (n-type)

 We know,

$$E_F = \left( \frac{E_d + E_c}{2} \right) + \frac{k_B T}{2} \ln \left[ \frac{N_d}{2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{\frac{3}{2}}} \right]$$

- We can say, from above equation that fermi level increases with increase in temperature.
- Now, as temperature increases, more donor atoms get positively ionised due to donation of electrons in conduction band and the fermi level lies between  $E_c$  and  $E_d$ .
- At a particular temperature, when all donor atoms are ionised, electron-hole pairs are generated due to breaking of covalent bonds. Thus, we can say that the fermi level gradually shifts towards the intrinsic fermi level  $E_i$ .



**Fig. 7**

- In the figure, the variation of fermi level with high and low donor concentration is indicated.
- From the figure, it is clear that shifting of fermi level with rise of temperature is slow in case of high donor concentration.

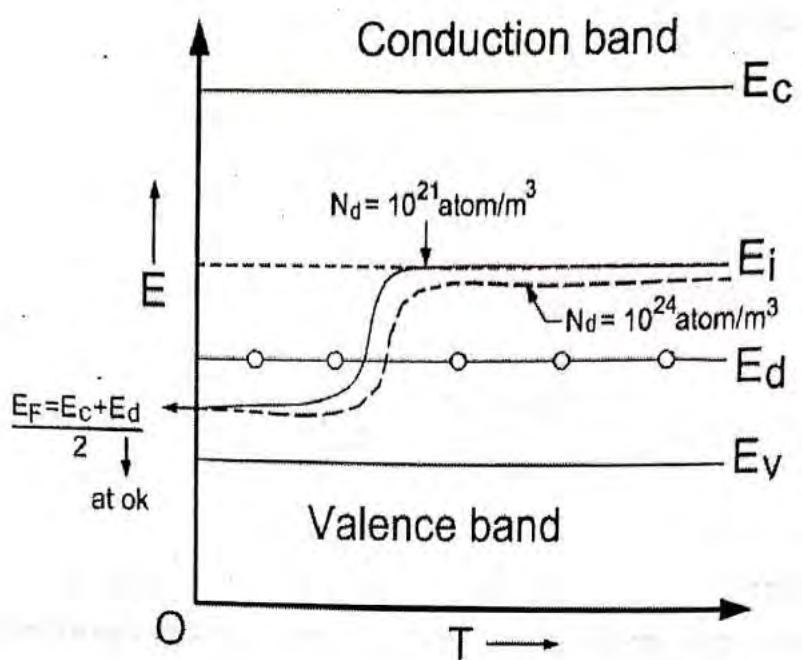
## 2.3.5.4 Variation of Fermi level with Temperature and Impurity concentration (P-type)

We know that



$$E_F = \frac{E_V + E_a}{2} - \frac{k_B T}{2} \ln \left[ \frac{N_a}{2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{\frac{3}{2}}} \right]$$

- From the above equation, it is seen that as temperature gets slowly increased, more and more acceptor atoms get negatively ionised due to transfer of electrons from valence band and fermi level lies between  $E_V$  and  $E_a$ .
- At a particular temperature, all acceptor atoms are ionised. Beyond this temperature, electron holes pairs are generated due to breaking of covalent bonds, and the material tries to behave as an intrinsic semiconductor.
- So, we can say that fermi level is gradually shifted towards the intrinsic level.



**Fig. 9**

- From the figure, it is seen that shifting of fermi level, with increase in temperaure is slow in case of heavily doped semiconductor. This is because, highly doped semiconductor will lose their extrinsic behaviour only at a very high temperature.

## 2.4 Carrier Generation and Recombination



### 2.4.1 Carrier Generation

*"It is a process where electron-hole pairs are created by exciting an electron from valence band to conduction band, thereby creating a hole in valence band."*

### 2.4.2 Recombination

*"Recombination is a reverse process where electrons and holes from conduction and valence band respectively recombine and are annihilated (destroyed)."*

- In the above process, both the carriers eventually disappear. The energy difference of initial and final stage of an electron is given off as phonons or photons.
- In semiconductors, many processes lead to generation and recombination. They are listed as below.

#### 2.4.2.1 Photon Transition (Optical generation/recombination)

- This is also known as direct recombination or band-to-band transition.
- An electron from conduction band falls back to valence band and releases energy in the form of photon.
- The reverse process i.e. generation of electron hole pairs is triggered by sufficiently energetic photon, which transfers its energy to a valence band electron, moving it to conduction band and leaving behind a hole valance band.
- Energy of incident photon has to be atleast of the magnitude of bandgap energy.

## Semiconductors

Below figure gives an overview of this process.

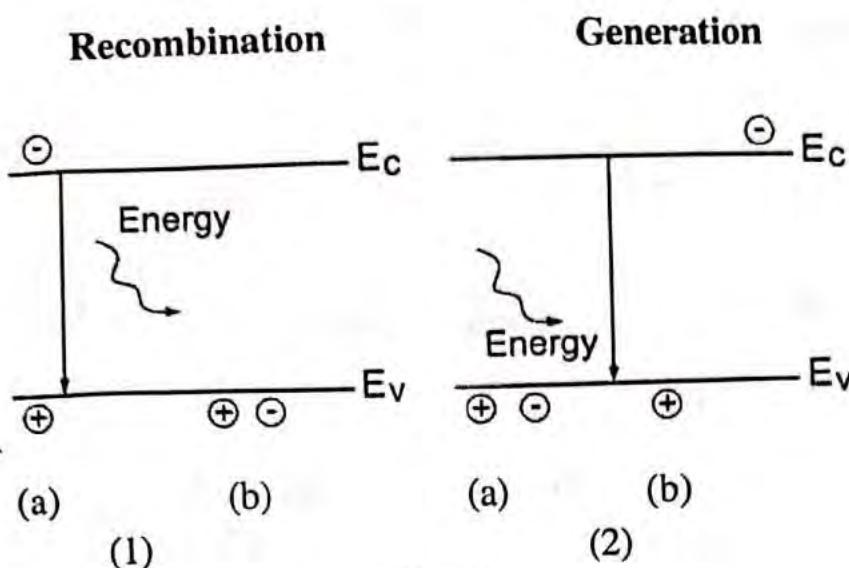


Fig. 10

- As shown in figure (2), initial electron-hole group (constellation) is found in (a) and after generation process, hole is created.
- As shown in figure (1), when electron moves to valence, the electron-hole constalation is found in (b).
- Now, for transitions from excited states to lower energy states, momentum has to be conserved. The energy absorbed or emitted by a photon is given by

$$E = h\nu$$

$h$  = Planck's constant

$\nu$  = frequency of emitted photon

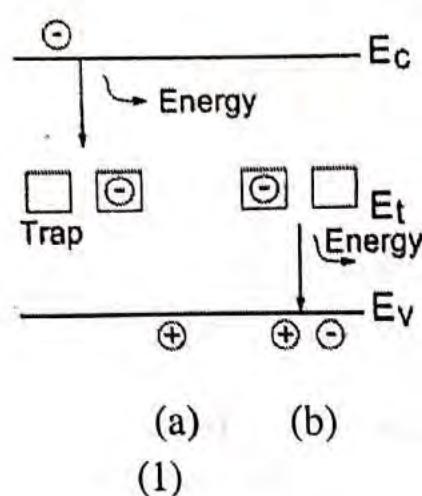
- As the momentum of photon is very small, no momentum transfer is possible, so only direct band-to-band transitions are possible, where no change of momentum is required.
- The process of recombination is directly proportional to the amount of available holes and electrons.
- The process always tries to achieve thermal equilibrium, i.e. In case of excess carrier concentration  $n_e \cdot n_h - n_i^2 > 0$ , carrier recombination dominate and for low carrier concentration  $n_e \cdot n_h - n_i^2 < 0$ , carrier generation dominates.

### 2.4.2.2 Phonon Transition (Shockley-Read-Hall (SRH) recombination)

- Also known as Indirect or Trap-assisted recombination.
- This process is trap assisted, passing through a lattice defect at energy level  $E_t$  within the semiconductor bandgap.

- The trap can be caused by presence of any foreign atom or structural defect is seen in the diagram, the process is

### Recombination



### Generation

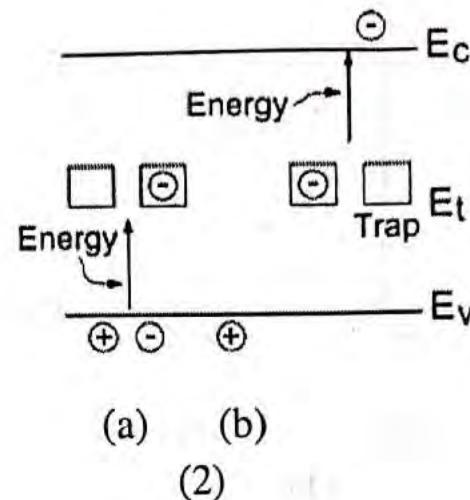


Fig. 11

#### (1) Electron capture

An electron from conduction band is captured by an empty trap in the band gap. This excess energy ( $E_c - E_t$ ) is transferred to the crystal lattice (phonon transmission).

#### (2) Hole capture

The trapped electron moves to valence band and neutralizes a hole (the hole is captured by trap). A phonon with energy ( $E_t - E_v$ ) is generated.

#### (3) Hole emission

An electron from valence band is trapped, leaving a hole in the valence band (hole is emitted from empty trap to valence band). Energy required is ( $E_t - E_v$ ).

#### (4) Electron Emission

A trapped electron moves from the trap energy level to conduction band.

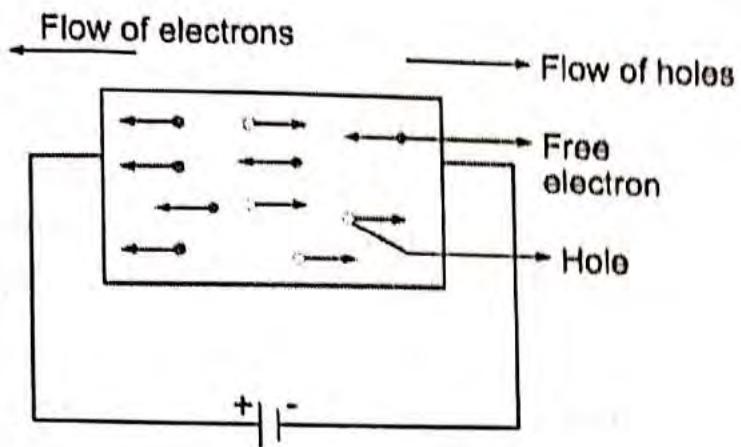
- The electron capture rate is proportional to the electron concentration in conduction band ( $n_h$ )
- hole capture rate is proportional to hole concentration in valence band.
- The hole and electron emission rates are proportional to concentration of empty traps and filled traps respectively.

## 2.5 Carrier Transport : Diffusion and Drift

### 2.5.1 Drift current

*"The flow of charge carriers, which is due to applied voltage or electric field is called drift current."*

- In a semiconductor, there are two types of charge carriers i.e. holes and electrons.
- When voltage is applied to a semiconductor, free electrons move towards the positive terminal of battery and holes move towards the negative terminal.



**Fig. 12**

- In a semiconductor, electrons always try to move in a straight line towards the positive terminal of battery. But due to continuous collisions with atoms, they change the direction of flow.
- Each time, the electron strikes an atom, it bounces back in random direction.
- The applied voltage does not stop the collisions, but causes, the electrons to drift towards the positive terminal.

The average velocity that an electron or hole achieves, due to applied voltage or electric field is called 'Drift velocity'.

Drift velocity of electrons is given by

$$V_e = \mu_e E$$

Drift velocity of holes is given by

$$V_h = \mu_h E$$

Drift current density due to free electrons is given by

$$J_e = n_e \mu_e E \text{ and}$$

Drift current density due to holes is given by

$$J_h = n_h \mu_h E$$

Total drift current density

$$J = J_e + J_h$$

$$= n_e \mu_e E + n_h \mu_h E$$

$$J = n_e E (\mu_e + \mu_h)$$

## 2.5.2 Diffusion current

The process by which charge carriers in a semiconductor move from a region of

higher concentration to a region of lower concentration is called 'Diffusion'.

- Region having more no. of electrons is called higher concentration region and that with less no. of electrons is called lower concentration region.  
*"Current produced due to the motion of charge carriers from a region of higher concentration to a region of lower concentration is called 'Diffusion current.'"*
- The above process occurs in semiconductors that are non-uniformly doped.
- Let us consider an *n*-type semiconductor with non-uniform doping as below.

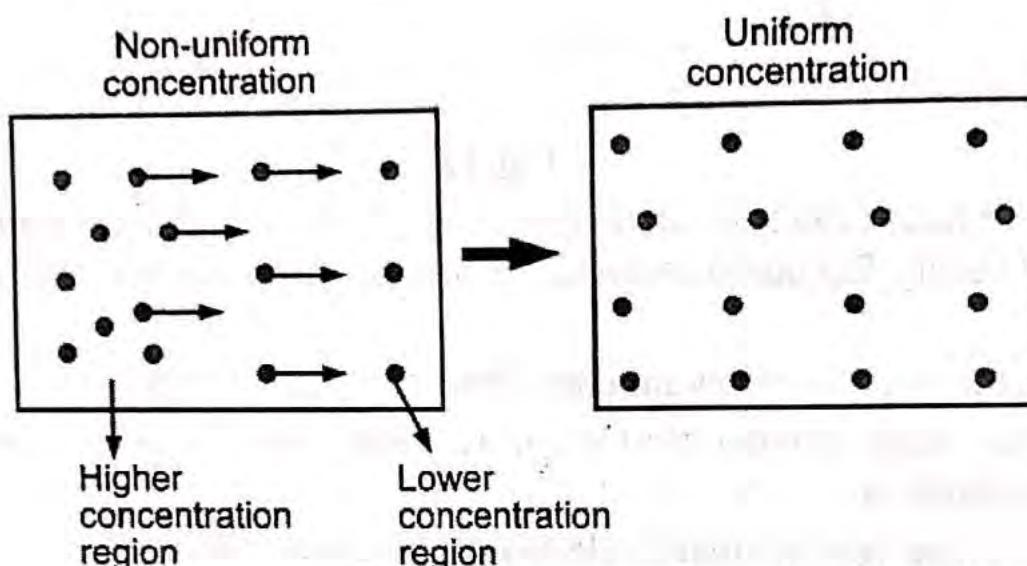


Fig. 13

- As seen in the figure, due to non-uniform doping, more no. of electrons are present on the left side, whereas lesser no. of electrons are present on the right side.
- The no. of electrons on the left side is more, as a result of which they will experience a repulsive force from each other. i.e. they tend to move to the right side to achieve uniform concentration of electrons.
- Electrons move from left side to right side and thus constitute a current, called 'Diffusion current.'
- Both Drift and Diffusion currents occur in semiconductors.
- Diffusion current occurs without an external voltage or electric field applied.

### 2.5.2.1 Concentration gradient

- Diffusion current density is directly proportional to the concentration gradient.
- Concentration gradient is the difference in concentration of electrons or holes in a given area. If it is high, diffusion current is also high and so current density is also high.

The concentration gradient for *n*-type semi conductor is given by

$$J_e \alpha \frac{dn_e}{dx}$$

The concentration gradient for p-type semiconductor is given by

$$J_h \alpha \frac{dn_h}{dx}$$

where,  $J_e$  = diffusion current density due to electrons  
 $J_h$  = diffusion current density due to holes

Diffusion current density due to electrons is given by

$$J_e = +e D_e \frac{dn_e}{dx}$$

where,  $D_e$  is the diffusion coefficient of electrons.

So, diffusion current density due to holes is given by

$$J_h = -e D_h \frac{dn_h}{dx}$$

where  $D_h$  is the diffusion coefficient of holes.

- Total current density due to electrons is the sum of drift and diffusion currents and is given by

$$J_e = \text{Drift current} + \text{Diffusion current}$$

$$J_e = en\mu_e E + eD_e \frac{dn_e}{dx}$$

Similarly, the total current density due to holes is the sum of drift and diffusion currents.

$$J_h = \text{Drift current} + \text{Diffusion current}$$

$$\therefore J_h = n_h e \mu_h E - eD_h \frac{dn_h}{dx}$$

## 2.6 P-N Junction

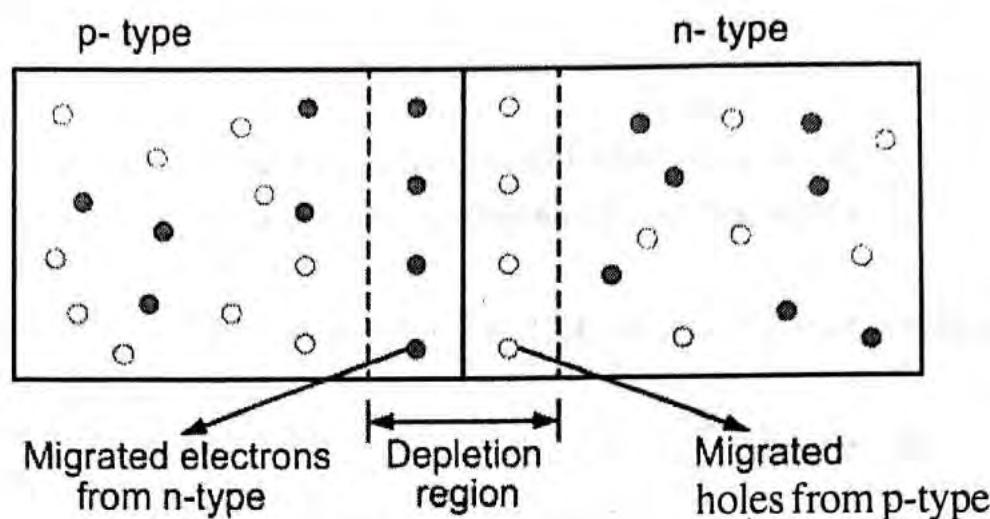
When a *p*-type semiconductor is fused (intimately joined) to an *n*-type semiconductor,

a *p-n* junction is formed.

- *P-N* junctions are fabricated by special processes like alloying, diffusion methods.

### 2.6.1 P-N Junction at Zero bias

- P-N Junction is as shown in the diagram below.



**Fig. 14**

- A *p*-type semiconductor has holes as majority charge carriers and *n*-type has electrons as majority charge carriers. In addition to these majority charge carriers, minority charge carriers are also present in both the types of semiconductors.
- The majority charge carriers near or at the junction, diffuse across the junction and recombine.
- After a few recombinations, the process stops.
- This is because the electrons crossing the junction are repelled by negative ions created and holes are repelled by positive ions created.
- The immobile ions, at the junction creates a zone that is devoid of charge carrier. (majority charge carriers).

*"This zone, depleted or devoid of charge carriers is called 'Depletion region'."*

- There is no current under this condition.
- The thickness of the depletion region is of an order of  $10^{-6}$  m.  
*"The potential difference across the depletion region is called 'Potential barrier'."*
- This potential barrier can be increased or decreased by applying voltage.

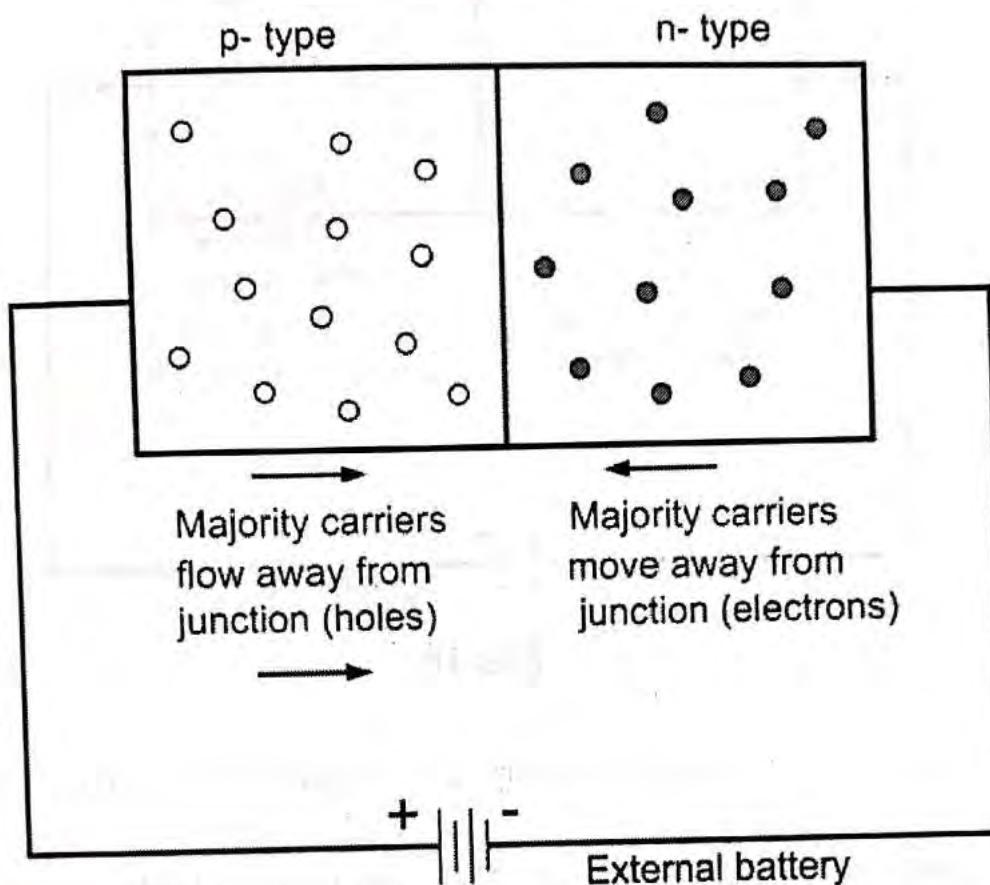
#### \* Working of a P-N Junction :

When an external voltage is applied to a P-N junction, it is said to be biased.

### 2.6.2 Forward Bias :

- Forward biasing is when we connect *p*-type to positive terminal of battery and *n*-type to negative terminal of battery.
- When the external voltage applied to a *p-n* junction cancels the potential barrier and permits

- the current, the junction is said to be in forward biased condition.
- When the forward bias is greater than the potential barrier, majority carriers move towards the junction, cross it and result in current.
- The current that flows due to majority carriers is called forward current. It increases with forward bias.



**Fig. 15**

### 2.6.3 Reverse Bias :

- Reverse biasing is when we connect positive terminal of battery to n-type and negative terminal of battery to p-type.
- When an external voltage applied to a p-n junction increases the potential barrier it is called in Reverse bias.
- What happens is that the applied reverse voltage, creates an electric field, which acts in the same direction of potential barrier.
- Due to this, the resultant field gets strengthened ie, potential barrier increases.
- This barrier prevents the flow of charge carrier across the junction.
- A very small current flows in the circuit due to the motion of minority carriers. This current is called 'Reverse current'

Depletion width increases

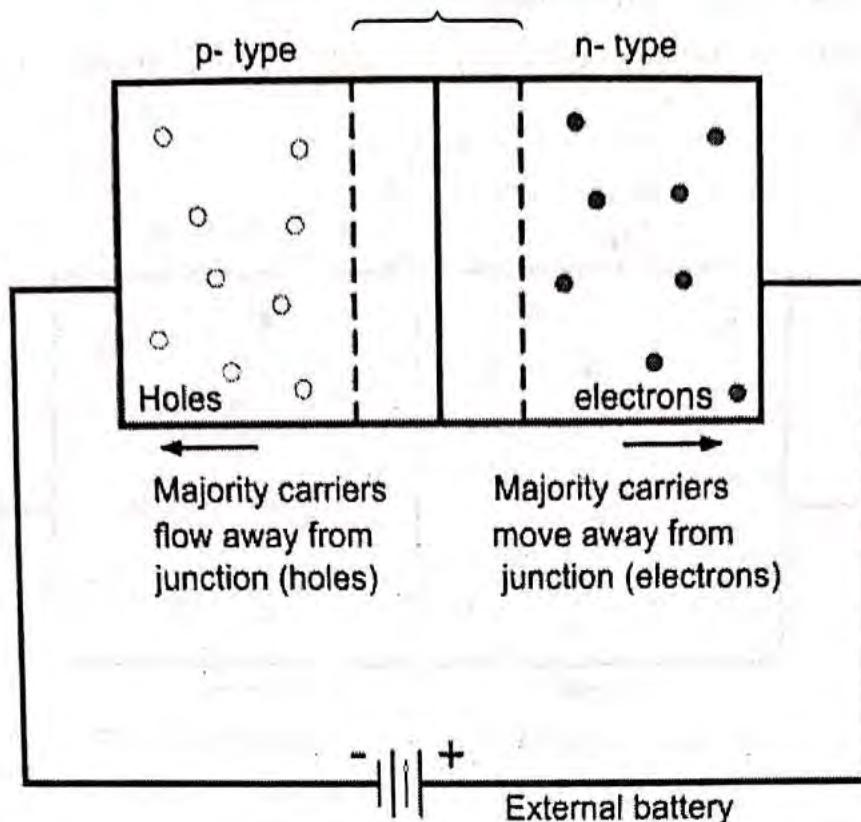


Fig. 16

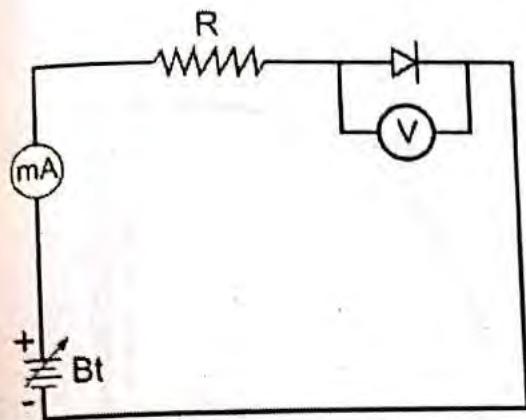
- When a *p-n* junction is forward biased, the junction has a low-resistance path and hence current flows in circuit.
- When a *p-n* junction is reverse biased, the junction has a high-resistance path and no current flows in circuit.
- Hence a *p-n* junction can be used as a switch or rectifier.  
It can also be used as clipper, clamper or in gates.

#### 2.6.4 Voltage-Current (V-I) characteristics of a *P-N* junction Diode :

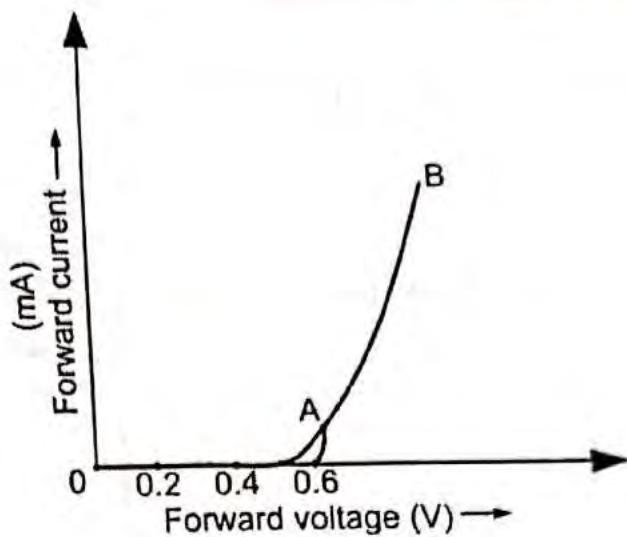
- The behaviour of a diode can be obtained by means of a graph known as volt-ampere or V-I characteristics.
- It is a graph between applied voltage across the terminals of a device and the current flowing through it.
- Characteristics of a diode can be studied under forward biasing and reverse biasing.

##### (a) Forward biasing of a diode :

- The circuit diagram for obtaining forward characteristics of a diode is as shown below.



(i)



(ii)

Fig. 17

- When the *p-n* junction diode is forward biased and if the applied voltage is gradually increased in steps, at some forward voltage ( $V_f$ ), the potential barrier is altogether eliminated and current starts flowing.  
(It is 0.3 V for *Ge* and 0.7V for *Si*)
- “*This voltage is known as threshold voltage ( $V_{th}$ )*” (Also called knee voltage or cut-in voltage)
- When milliammeter readings are noted at various steps of applied voltage and a graph is plotted, it is as shown in above fig. (19.2).
- It is seen from the graph that no current flows till the barrier voltage is overcome. This is shown as point *A* in graph.
- Once the external voltage exceeds the barrier potential, the current increases exponentially as shown by portion *AB* of graph. This is called the linear operating region of diode.

At point *A*, we can say that

$$V_f = V_{th} = V_B \quad (V_B = \text{Barrier potential})$$

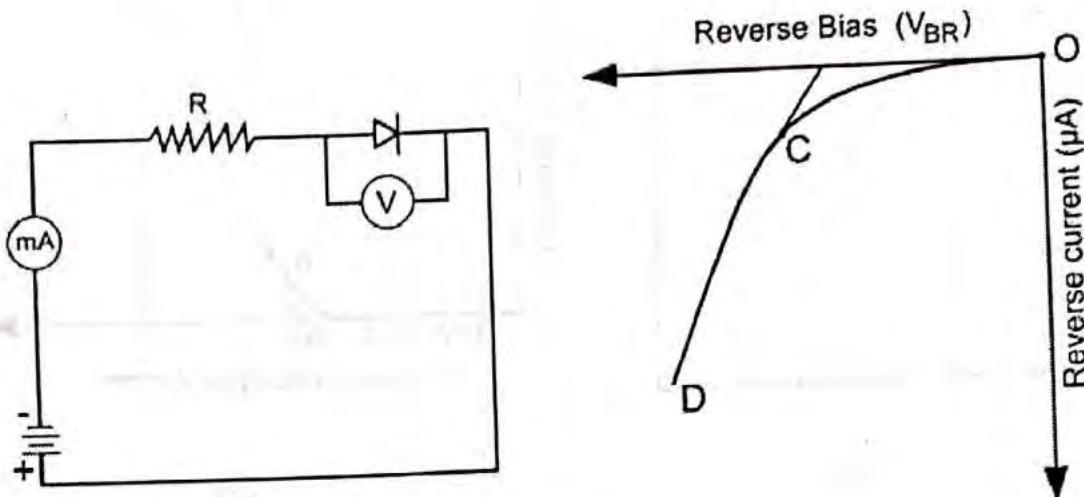
Forward resistance can be calculated as

$$R_f = \frac{\Delta V_f}{\Delta I_f}$$

- If the forward voltage is increased beyond the safe limit, damage of diode is likely to occur due to overheating.

### (b) Reverse biasing of a diode

- The circuit diagram for plotting reverse characteristics of a diode is as shown below.



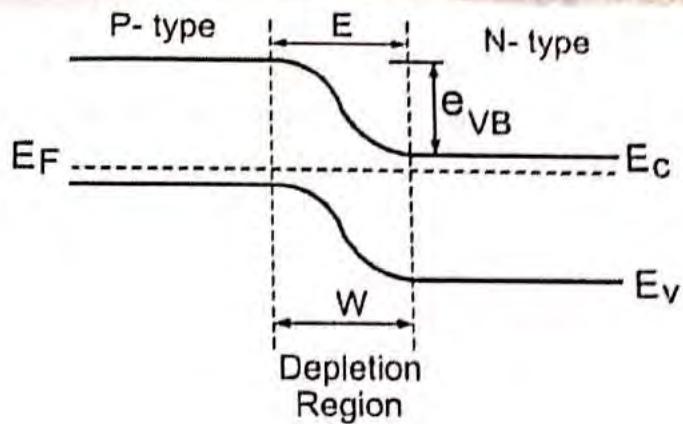
**Fig. 18**

- When a p-n junction is reverse biased, majority carriers are blocked and only a small current due to minority carriers flows through the diode.
- As the reverse voltage is increased in suitable steps, reverse current reaches its maximum or saturation value. This is called reverse saturation current or leakage current.
- The diode current is recorded at each step and a graph is plotted as shown in figure (2).
- As seen in the graph, a curve OCD is obtained. This OCD curve is the reverse characteristic of the diode.
- When the breakdown voltage is more than the applied voltage, diode current is very small and almost a constant as seen by portion OC.
- When external voltage exceeds the breakdown voltage, current sharply exceeds. This curve CD is called the zero resistance path.
- Reverse current is of an order of ( $\mu\text{A}$ ) for Ge and ( $\text{nA}$ ) for Si.

- Resistance of diode from the curve is  $R_r = \frac{\Delta V_r}{\Delta I_r}$ .

### 2.6.5 Energy band diagram of P-N junction

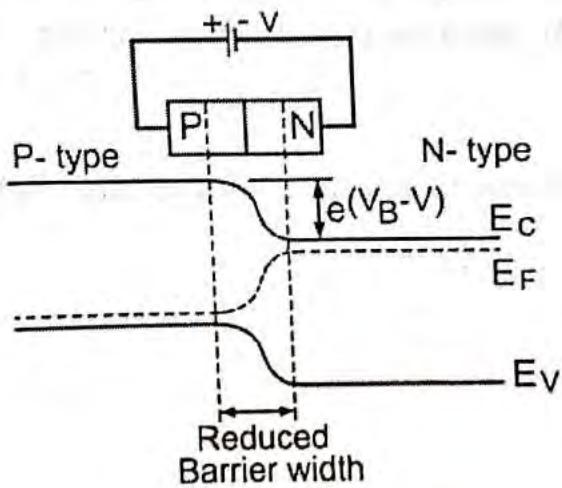
#### (a) Zero Bias (At equilibrium)



**Fig. 19**

- The fermi level in *p*-type is close to the valence band and in *n*-type is close to the conduction band.
- When the *P-N* junction is formed, the majority charge carriers near or at the junction diffuse across the junction and recombine, till the fermi level on both sides equalizes.
- The conduction band in *P* region is above the conduction band in *N* region, by a factor  $e \cdot V_B$  (where  $V_B$  is the potential barrier across junction).
- The majority charge carriers in *N*-region face the potential barrier and hence cannot cross the junction. So, there is no current flow.

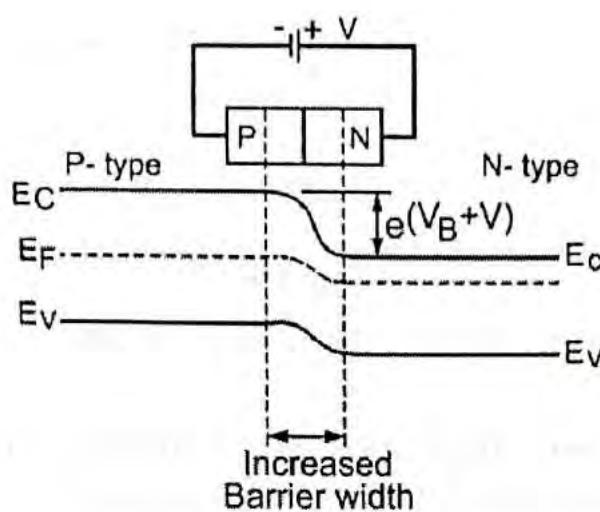
### (b) Forward Bias



**Fig. 20**

- An external battery of voltage  $V$ , with its positive connected to P-type and negative connected to N-type is connected.
- The energy of electrons in N region, increases by  $eV$  (as N-type is connected to -ve terminal).

- Now, the fermi level rises by a factor  $eV$  and hence potential barrier is reduced to  $e(V_B - V)$  and the barrier width is reduced.
  - The electrons thus face a reduced potential and can cross the junction.
  - For the current flow, the applied potential should be greater than barrier potential.
- (c) Reverse Bias**



**Fig. 21**

- The external battery with voltage  $V$  is connected, with its positive connected to N-region and negative connected to P-region.
- The energy of electron now reduces by  $eV$ . So the fermi level is shifted down by a factor  $eV$  and potential barrier increases to  $e(V_B + V)$ , thereby increasing barrier width.
- It now becomes difficult for electrons to cross the junction, so there is no current flow. However, a very small current can flow due to the minority charge carriers ( $\mu\text{A}$  in Ge and  $\text{nA}$  in Si)

## 2.7 Metal – Semiconductor Junction (Ohmic and Schottky)

### \* Work function ( $\phi$ )

It is the minimum energy required to transfer an electron from a point within a solid to a point just outside its surface. (or the vacuum immediately outside the solid surface).

### \* Electron affinity ( $\chi_n$ )

It is defined as the amount of energy released or spent when an electron is added to a neutral atom or molecule.

(It is the likelihood of a neutral atom, gaining an electron).

- When a metal and semiconductor are brought into contact, there are two types of junctions formed, depending on the work function of semiconductor and its relation with metal.

$\phi_m > \phi_{semi} \Rightarrow$  Schottky junction

$\phi_m < \phi_{semi} \Rightarrow$  Ohmic junction

### 2.7.1 Schottky contact ( $\phi_m > \phi_{semi}$ )

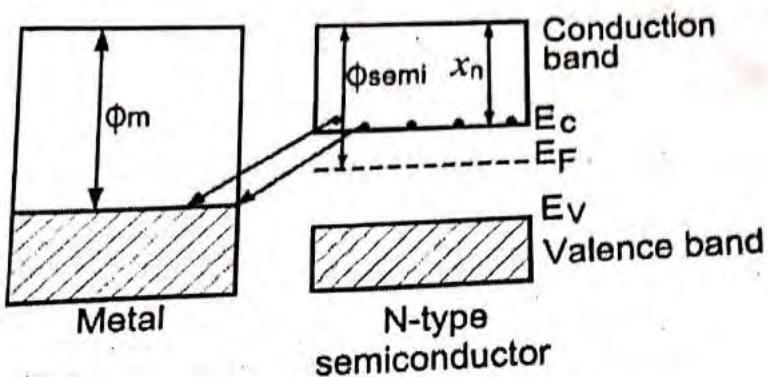


Fig. 22

As seen in the figure, the fermi level of semi-conductor is higher than metal (since work function is lower)

- When the contact is made, the fermi levels should line up at equilibrium.
- When the contact is formed, due to low charge density on semiconductor side (approx  $10^{17} / \text{cm}^3$ ), electrons are removed not only from the surface, but also from certain depth of semiconductor. This leads to a formation of depletion region in the semiconductor.
- The fermi level lines up and a positive potential is created on semiconductor side and a negative potential on metal side.
- Band bends up in the direction of electric field.

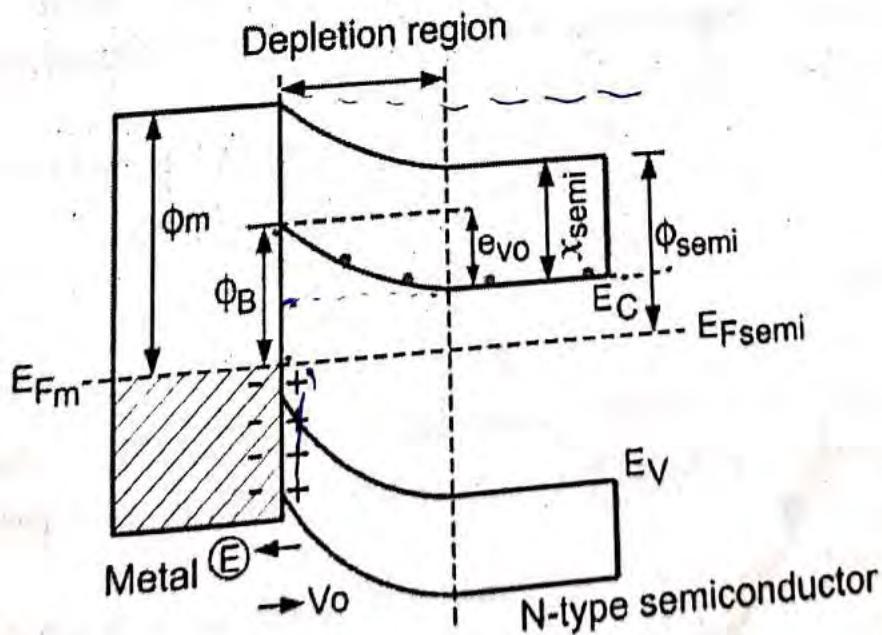


Fig. 23

- There is a built-in potential in Schottky junction, given by the difference of work functions.

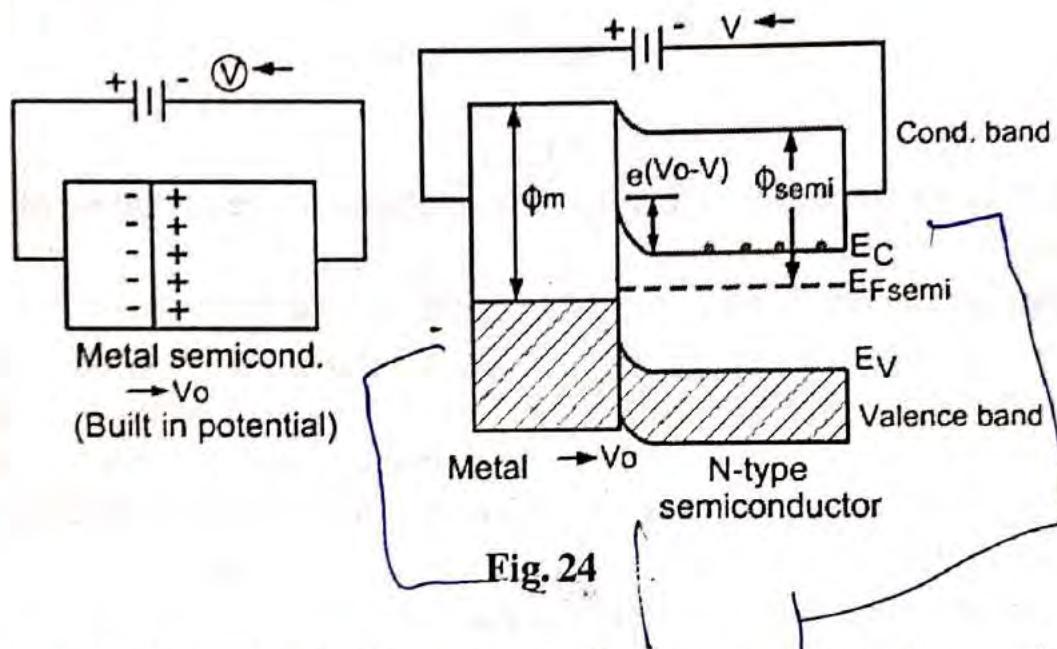
$$\phi_m - \phi_{semi} = eV_0$$

- This contact potential acts as a barrier for electrons to move from semiconductor to metal.
- When the contact was made, electrons moved to metal side and formed a depletion region which prevents further motion of electrons.
- This is the Schottky barrier, denoted by

$$\phi_B = (\phi_m - \phi_{semi}) + (E_C - E_{F_n})$$

$$\phi_B = (\phi_m - \chi_n) \quad (\chi_n \text{ is the electron affinity of semiconductor})$$

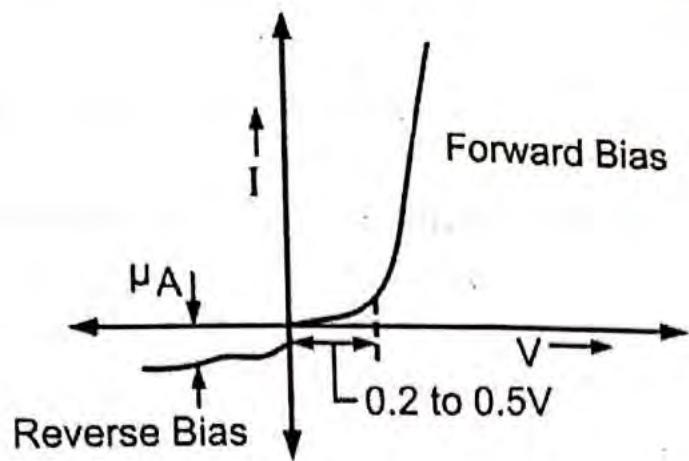
### (a) Forward Bias



- The external voltage is applied in such a way that it opposes the built-in potential.
- The fermi levels no longer line up, but are shifted. The magnitude of the shift depends on the applied voltage.
- The depletion layer is thus narrowed and electrons move from semiconductor to metal.
- A large current, exponentially related to 'V' now starts flowing

### (b) Reverse Bias

- In this case, the external potential, applied is in the same direction as built-in potential.
- Again, the fermi levels do not line up, but the barrier for electron motion from n-type metal becomes higher.
- The applied voltage adds on to the built-in potential and depletion region gets wider.
- The I-V characteristics of Schottky junction are as shown below.



**Fig. 25**

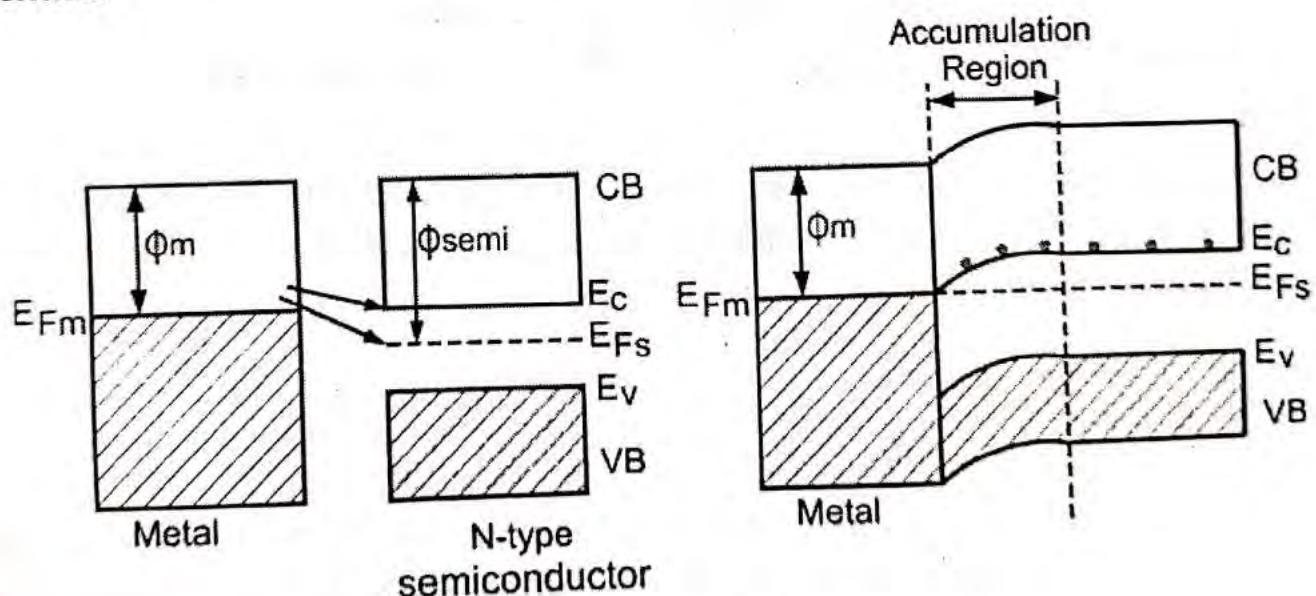
From the graph, we can say that it is a rectifying junction as it allows current flow in only one direction.

### - Applications

Rectifiers, voltage clamps, Rectifying high frequency signals, RF mixer and detector.

### 2.7.2 Ohmic Contact

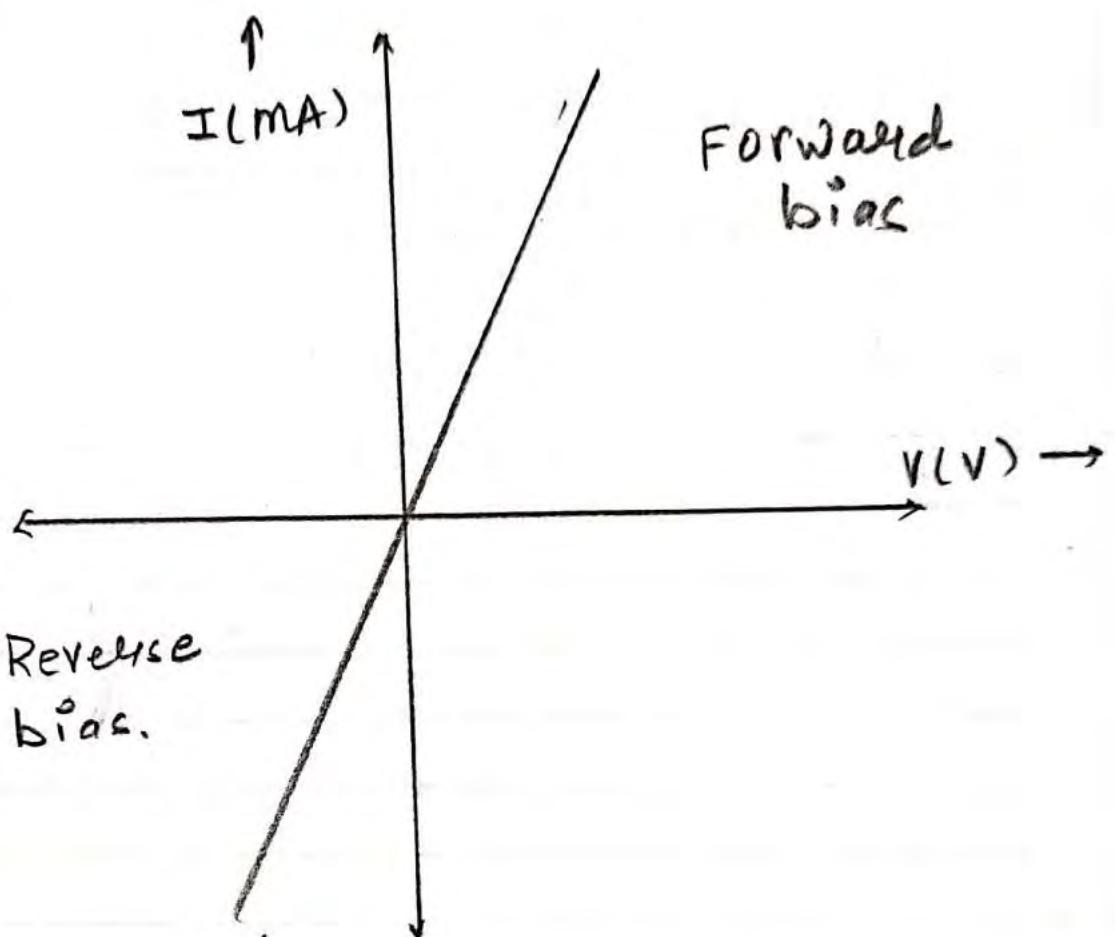
- When the semiconductor has a higher work function than metal, an ohmic junction is formed.



**Fig. 26**

- At equilibrium, the fermi levels line up. The electrons move from the metal to the semiconductor (i.e. empty states in conduction band) and there is an accumulation region near the interface.
- The accumulation region has a higher conductivity due to higher concentration of electrons.

For Ohmic contact



[fig. I-V characteristics of Ohmic Junction]

- Thus the Ohmic junction acts as a resistor, conducting in both forward and reverse bias.
- **Applications**
- It is used in thermoelectric devices (coding a small volume, by applying electric currents)

## 2.8 Semiconductor materials of interest for optoelectronic devices

- When photons of energy equal to or greater than the band gap energy are incident on a semi-conductor, electrons from the valence band are excited to conduction band, thereby creating electron-hole pairs.

### (a) Photoconductivity

*"The increase in conductivity of a material due to EHP (Electron-Hole Pairs) arising from optical excitation is called photoconductivity."*

- This is used in devices like photodiodes.

### (b) Luminescence :

*"The property of light emission is called luminescence."*

- Different types of luminescence processes on the basis of excitation mechanisms.

#### (1) Photoluminescence :

When electrons are excited by the absorption of photons of suitable frequency and energy equal to or greater than bandgap, the resulting radiation due to recombination of electron-hole pairs is called Photoluminescence.

Sub processes are

|                 |   |         |
|-----------------|---|---------|
| Phosphorescence | } | used in |
| Fluorescence    |   |         |

#### (2) Cathodoluminescence :

When electron-hole pairs are generated by bombardment of highly energetic electrons into the material, the resulting radiation, due to recombination of electron-hole pairs is called cathodeluminescence

eg. Television tubes, CRT's

#### (3) Electroluminescence (EL) :

When the excitation of carriers (generation of electron-hole pairs) is produced due to the introduction of forward current into the material, the resulting radiation due to recombination of electron-hole pairs is called Electroluminescence.

eg. LED's

Basically, optoelectronic devices are divided into two categories.

#### (1) The ones which convert electrical current into electromagnetic radiation (light)

eg. LED's

## Semiconductors

- (2) The ones which convert light into electric current.  
eg. Photodiode.

### 2.8.1 LED's (Light Emitting Diodes)

"It is a two-lead semiconductor device which emits light, when electrons (from conduction band) recombine with holes (in valence band)."

- LED's are basically  $p-n$  junctions that are made from a very thin layer of fairly heavily doped semiconductor material and depending on the semiconductor material used, and the amount of doping, when forward biased, an LED emits light of a specific wavelength.

Some examples of semiconductors used to make LED's

- |  |                           |
|--|---------------------------|
| (1) Ga As (Gallium Arsenide)             | - Infrared (850 - 940 nm) |
| (2) Ga As P (Gallium Arsenide Phosphide) | - Red (630 - 660 nm)      |
| (3) Ga P (Gallium Phosphide)             | - Yellow (585 - 595 nm)   |
| (4) AlGa P (Aluminium Gallium Phosphide) | - Green (550 - 570 nm)    |
| (5) SiC (Silicon carbide)                | - Blue (430 - 505 nm)     |

\* Working of LED (Basic working principle is Electroluminescence)

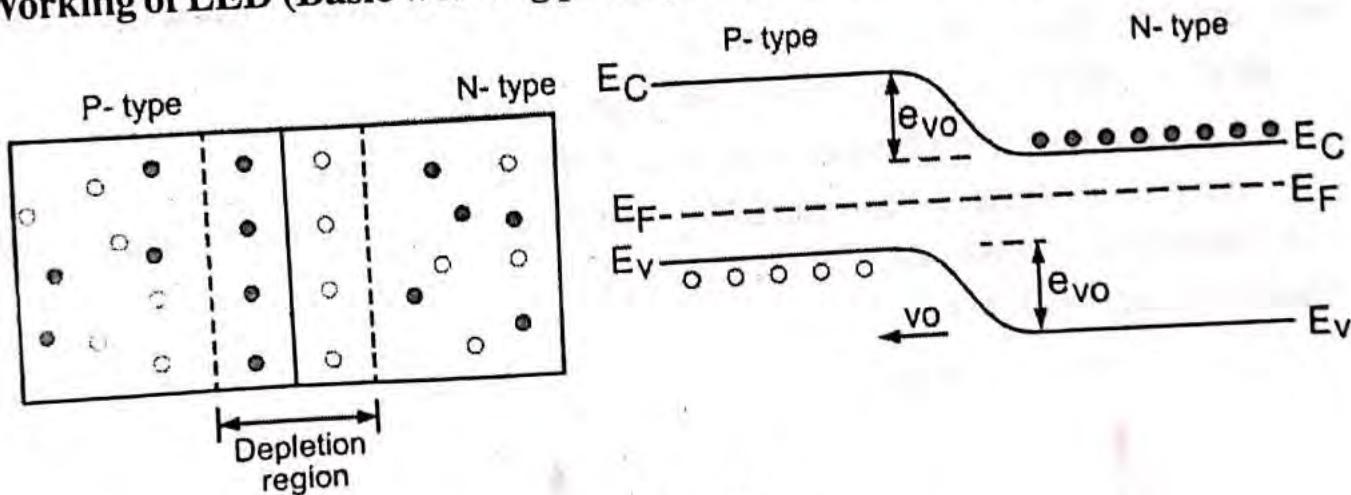


Fig. 27

- As seen in the diagram, the fermi levels line up in equilibrium. There is a built-in potential due to which, electrons from  $n$ -side are not able to cross the junction.
- There is a built-in potential and a depletion region.

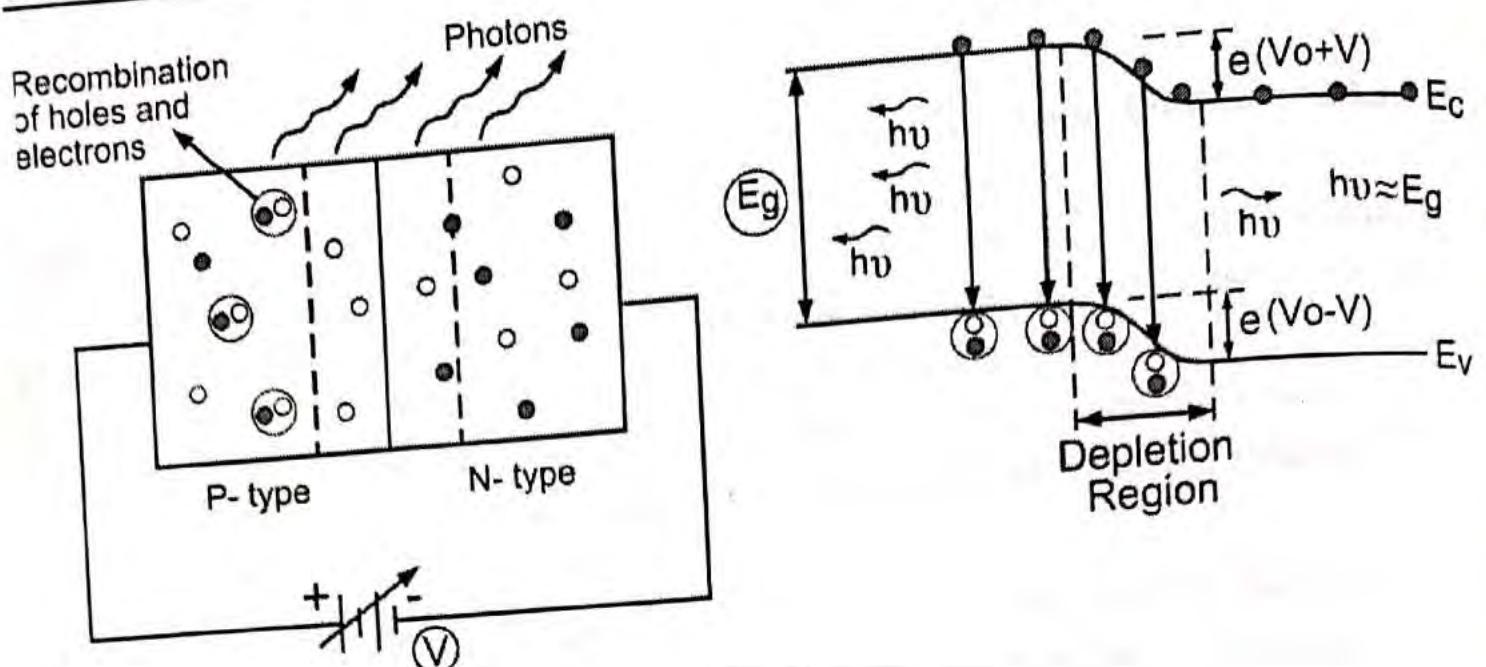


Fig. 28

- When an external forward voltage is applied to an LED, the width of depletion layer decreases on increasing applied voltage.
- The electrons, now have sufficient energy to overcome (cross) the potential barrier.
- These electrons, on crossing the barrier, recombine with holes and release the difference of energy ( $E_C - E_V$ ) in the form of photons.
- Each recombination of carriers, emits some light.
- The energy of the photons depends on the forbidden energy gap.
- When the forward bias applied to an LED is small, the intensity of emitted light is small. As the forward current increases, the emitted light also increases.

#### \* Characteristics of LED

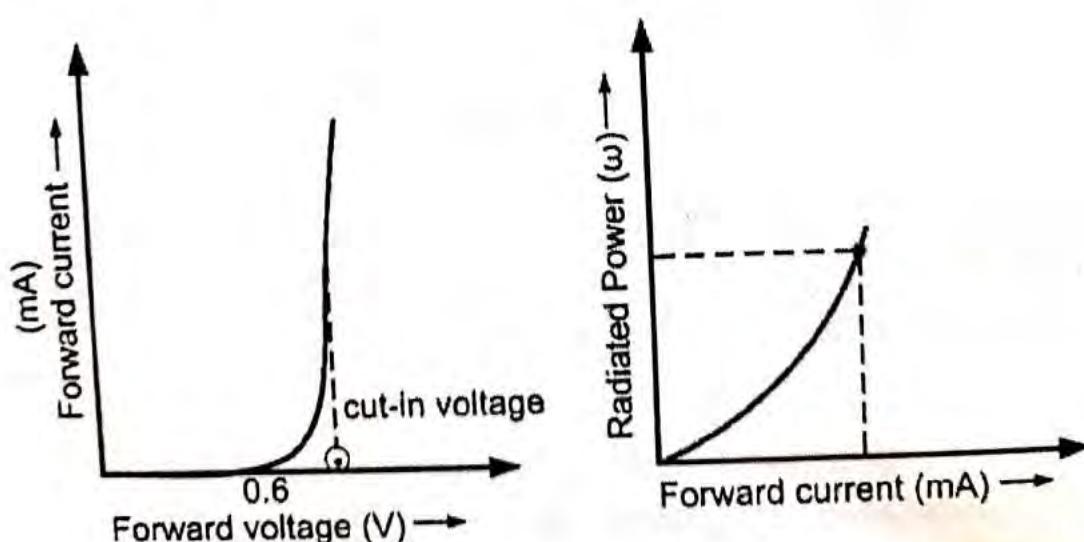


Fig. 29

- ~~Semiconductors~~
- From the above figure (a), it is seen that current increases exponentially, after a certain voltage.
  - Till then, due to potential barrier, current is almost zero.
  - From figure (b), it is clear that amount of output light is directly proportional to the forward current.

### **Applications :**

- (1) Camera flashes
- (2) Traffic signals
- (3) General lighting
- (4) Medical devices

## **2.8. 2 Photodiodes**

*"A photodiode is a semiconductor device that converts light into electric current."*

- Materials used in the construction of photodiodes.

eg. Silicon (Si)  
Germanium (Ge)  
Indium Arsenide Antimeneide (InAsSb)  
Indium Gallium Arsenide (InGaAs)

- The working principle of Photodiode is "Photoelectric effect":

### **Working :**

- A normal  $p-n$  junction diode allows a small amount of electric current under reverse bias.
- To increase the current under reverse bias, there should be more minority carriers.
- The external voltage (reverse voltage) will supply energy to minority carriers, but cannot increase their population.
- The minority carriers generated due to external reverse bias voltage at the  $n$  and  $p$ -side recombine in the same material before they cross the junction. As a result, no current flows.
- So, to increase the charge carriers in the depletion region, light (photons) is used as an external energy source.

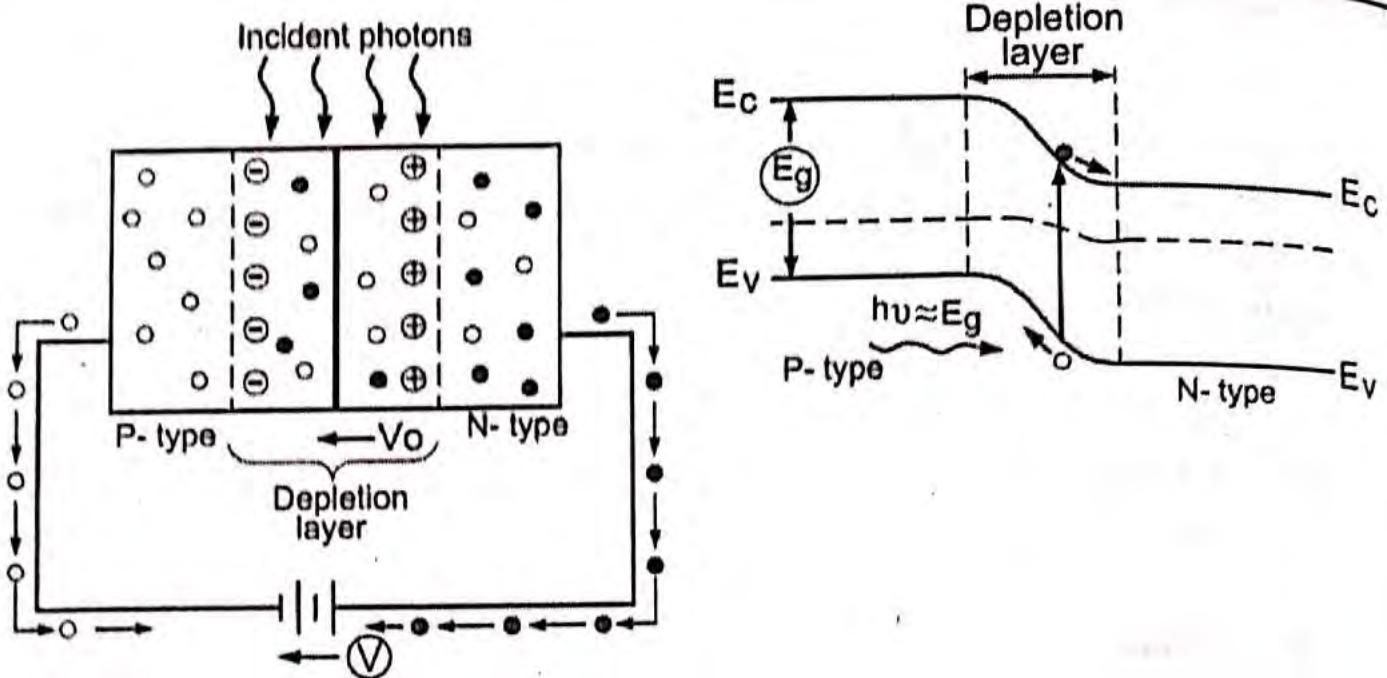


Fig. 30

- When no light is applied to the photodiode, a very small current flows due to the applied voltage. This small electric current is called 'Dark current'
- The reverse current in photodiode is independent on the reverse voltage, rather it depends only on the light intensity.
- When light is incident on the photodiode (having energy  $\approx E_g$ ), electron-hole pairs are created in the depletion layer as shown in the above diagram.
- Most of the electric current is generated by charge carriers in the depletion layer as they have high drift and low recombination rates.
- The current generated in photodiode due to application of light is called photocurrent.
- Total current is the sum of dark current and photocurrent.
- The electric current generated is directly proportional to the no. of incident photons.

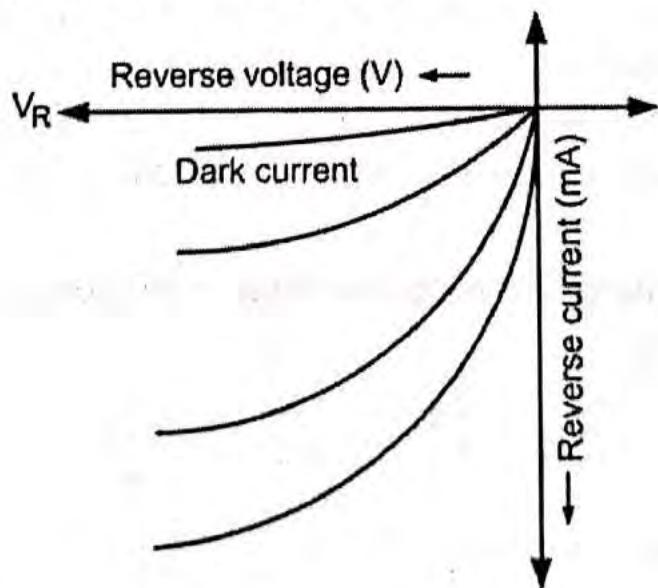


Fig. 34

## V.I. Characteristics

Photocurrent depends on light intensity as shown in graph.

### **Applications :**

- (1) Smoke detectors
- (2) Photo sensor
- (3) CD Players, remote controls

## Numericals

- 1) For an intrinsic silicon, room temperature electrical conductivity is  $4 \times 10^{-4} \text{ } \Omega m^{-1}$ . Electron and hole mobilities are  $0.14 \text{ } m^2/V\text{sec}$  and  $0.040 \text{ } m^2/V \text{ sec}$ . respectively. Calculate the electron and hole concentration at room temp.

Solution :

$$\sigma_i = 4 \times 10^{-4} \text{ } \Omega m^{-1}, \mu_e = 0.14 \text{ } m^2/V\text{sec}, \mu_h = 0.04 \text{ } m^2/V\text{sec}$$

We know,

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

$$\therefore n_i = \frac{\sigma_i}{e(\mu_e + \mu_h)}$$

$$= \frac{4 \times 10^{-4}}{(1.6 \times 10^{-19})(0.14 + 0.040)}$$

$$\therefore n_i = \frac{4 \times 10^{-4}}{2.88 \times 10^{-20}}$$

$$\therefore n_i = 1.38 \times 10^{16} / m^3$$

From law of mass action, we have  $n_e = n_h = n_i$

$$\therefore n_e = n_h = 1.38 \times 10^{16} / m^3$$

Answer

- 2) The intrinsic carrier density at room temperature in Germanium is  $2.37 \times 10^{19} / m^3$ . If electron and hole mobilities are  $0.38$  and  $0.18 \text{ } m^2/V\text{sec}$  respectively, find out its resistivity.

Solution :

Semiconductors

$$n_i = 2.37 \times 10^{19} / m^3, \quad \mu_e = 0.38 \text{ m}^2 / V \text{ sec}, \quad \mu_h = 0.18 \text{ m}^2 / V \text{ sec}$$

We know,  $\sigma_i = n_i e (\mu_e + \mu_h)$

$$\therefore \rho = \frac{1}{\sigma_i} = \frac{1}{n_i e (\mu_e + \mu_h)}$$

$$\therefore \rho = \frac{1}{(2.37 \times 10^{19})(1.6 \times 10^{-19})(0.38 + 0.18)}$$

$$\therefore \rho = \frac{1}{2.123}$$

$$\therefore \rho = 0.471 \Omega m$$

*Answer*

- 3) The electron and hole mobilities in intrinsic antimony are 6 and  $0.2 \text{ m}^2/\text{V.sec}$  respectively. At room temperature, resistivity is  $2 \times 10^{-4} \Omega \text{m}$ . Assuming the material is intrinsic, determine its intrinsic carrier density at room temp.

$$\rho = 2 \times 10^{-4} \Omega \text{m}, \quad \mu_o = 6 \text{ m}^2 / \text{V.sec}, \quad \mu_h = 0.2 \text{ m}^2 / \text{V.sec}$$

$$n_i = ?$$

**Solution**

We know,

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

$$\therefore n_i = \frac{\sigma_i}{e (\mu_e + \mu_h)}$$

$$\therefore n_i = \frac{1}{\rho e (\mu_e + \mu_h)}$$

$$= \frac{1}{(2 \times 10^{-4})(1.6 \times 10^{-19})(6 + 0.2)}$$

$$\therefore n_i = 5.04 \times 10^{21} / m^3$$

*Answer*

- 4) For a silicon semiconductor, with  $E_g = 1.12 \text{ eV}$ , determine the position of fermi level at 300 K, if  $m_e^* = 0.12 m_o$  and  $m_h^* = 0.28 m_o$ . ( $m_o$  = rest mass of an electron)

$$E_g = 1.12 \text{ eV} = 1.12 \times 1.6 \times 10^{-19} \text{ J}$$

$$m_e^* = 0.12 m_o, \quad T = 300 \text{ K}, \quad m_h^* = 0.28 m_o, \quad E_F = ?$$

## Solution

We know,

$$E_F = \frac{E_g}{2} + \frac{3k_B T}{4} \ln\left(\frac{m_h^*}{m_e^*}\right)$$

$$= \frac{1.12 \times 1.6 \times 10^{-19}}{2} + \frac{3}{4} (1.38 \times 10^{-23} \times 300) \times \ln\left(\frac{0.28m_o}{0.12m_o}\right)$$

$$= 8.96 \times 10^{-20} + \frac{3}{4} (4.14 \times 10^{-21}) \times 0.84729$$

$$\therefore E_F = 9.22 \times 10^{-20} J \quad \text{or} \quad E_F = 0.5764 eV$$

*Answer*

- 5) Suppose that effective mass of holes in a material is 4 times that of electrons. At what temperature would the fermi level be shifted by 10% from the middle of forbidden energy gap. Given  $E_g = 1 eV$ .

Solution

$$m_h^* = 4m_o, \quad E_g = 1eV = 1.6 \times 10^{-19} J, \quad m_e^* = m_o$$

$$E_F = \frac{E_c + E_v}{2} + \frac{3k_B T}{4} \ln\left(\frac{m_h^*}{m_e^*}\right) \quad \dots(1)$$

$$\text{At } T = 0K, E_F = \frac{E_c + E_v}{2} = \frac{E_g}{2}$$

So, we can take

$$E_F = (E_v + 0.5)eV$$

$$\therefore (E_v + 0.5) = \frac{E_c + E_v}{2}$$

At any temperature T.K. fermi level is shifted by 10%, i.e. 0.1 eV

$$E_F = (E_v + 0.6)eV$$

$$\therefore (E_v + 0.6) = \frac{E_c + E_v}{2} + \frac{3k_B T}{4} \ln\left(\frac{m_h^*}{m_e^*}\right) \quad \dots(2)$$

Subtracting (1) from (2),

$$0.1 \text{ eV} = \frac{3}{4} k_B T \ln 4$$

$$\therefore 0.1 \text{ eV} = \frac{3}{4} (1.38 \times 10^{-23}) \times T \times \ln 4$$

$$\therefore T = \frac{4 \times 0.1 \text{ eV}}{3(1.38 \times 10^{-23})(\ln 4)}$$

$$\therefore T = \frac{4 \times 0.1 \times 1.6 \times 10^{-19}}{3(1.38 \times 10^{-23})(0.602)}$$

$$\therefore T = 1115.12 \text{ K}$$

**Answer**

- 6) Find the resistance of an intrinsic Germanium rod 1 cm long, 1 mm wide and 1 mm thick at 300 K. For  $n_i = 2.5 \times 10^{19} / \text{m}^3$ ,  $\mu_e = 0.39 \text{ m}^2 / \text{V.sec}$ ,

$$\mu_h = 0.19 \text{ m}^2 / \text{V.sec}$$

**Solution**

$$l = 1 \text{ cm} = 10^{-2} \text{ m}, \quad b = 1 \text{ mm} = 10^{-3} \text{ m}, \quad t = 1 \text{ mm} = 10^{-3} \text{ m}$$

$$T = 300 \text{ K}, \quad \mu_e = 0.39 \text{ m}^2 / \text{V.sec}, \quad \mu_h = 0.19 \text{ m}^2 / \text{V.sec}, R = ?$$

$$\begin{aligned} \sigma_i &= n_i e (\mu_e + \mu_h) \\ &= (2.5 \times 10^{19})(1.6 \times 10^{-19})(0.39 + 0.19) \end{aligned}$$

$$\therefore \sigma_i = 2.32 \Omega \text{m}^{-1} \quad [A = \text{breadth} \times \text{thickness}]$$

$$= (10^{-3} \times 10^{-3} \text{ m}^2)]$$

$$\text{We know, } R = \frac{\rho l}{A} = \frac{l}{\sigma A}$$

$$\therefore R = \frac{10^{-2}}{2.32(10^{-3} \times 10^{-3})}$$

$$\therefore R = 4310 \Omega$$

**Answer**

## Numericals

- 13) In a *p*-type Ge,  $n_i = 2.1 \times 10^{19} / m^3$ , density of boron =  $4.5 \times 10^{23}$  atoms/m<sup>3</sup>. The electron and hole mobilities are 0.4 and 0.2 m<sup>2</sup>/V.sec respectively. What is its conductivity before and after addition of boron atoms?

$$n_i = 2.1 \times 10^{19} / m^3$$

$$\mu_e = 0.4 m^2 / v \cdot sec, \quad \mu_h = 0.2 m^2 / v \cdot sec,$$

$$n_{boron} = 4.5 \times 10^{23} / m^3$$

**Solution**

Before adding boron, conductivity of Germanium, the semiconductor is intrinsic

$$\begin{aligned}\therefore \sigma_i &= n_i e (\mu_e + \mu_h) \\ &= 2.1 \times 10^{19} \times 1.6 \times 10^{-19} (0.4 + 0.2)\end{aligned}$$

$$\therefore \sigma_i = 2.016 \Omega m^{-1}$$

**Answer**

Now, after adding boron, it becomes a *p*-type semiconductor,

$$\begin{aligned}\text{Conductivity} \quad \sigma_b &= n_{boron} e \cdot \mu_h \\ &= 4.5 \times 10^{23} \times 1.6 \times 10^{-19} \times 0.2 \\ \therefore \sigma_b &= 1.44 \times 10^4 \Omega m^{-1}\end{aligned}$$

**Answer**

- 14) Find the concentration of holes and electrons in *n*-type silicon at 300K. If the conductivity is  $3 \times 10^4 \Omega m^{-1}$ . Also find these values of *p*-type silicon.

$$n_i = 1.5 \times 10^{16} / m^3$$

$$\mu_e = 1300 \times 10^{-4} m^2 / V \cdot sec, \quad \mu_h = 500 \times 10^{-4} m^2 / V \cdot sec,$$

**Solution**

We have

$$n_i = 1.5 \times 10^{16} / m^3 \quad \mu_e = 1300 \times 10^{-4} m^2 / V \cdot sec,$$

$$\mu_h = 500 \times 10^{-4} m^2/V \cdot \text{sec},$$

$$\sigma = 3 \times 10^4 \Omega^{-1} m^{-1}$$

$$n_e = ?$$

$$n_h = ?$$

Density of electrons in *n*-type silicon is

$$n_e = \frac{\sigma}{e\mu_e} = \frac{3 \times 10^4}{1.6 \times 10^{-19} \times 1300 \times 10^{-4}}$$

$$\therefore n_e = 1.44 \times 10^{24} \text{ electrons/m}^3$$



**Answer**

Density of holes is

$$n_h = \frac{n_i^2}{n_e} = \frac{(1.5 \times 10^{16})^2}{1.44 \times 10^{24}}$$

$$\therefore n_h = 1.56 \times 10^8 \text{ holes/m}^3$$

**Answer**

Density of holes for *p*-type

$$n_h = \frac{\sigma}{e\mu_h} = \frac{3 \times 10^4}{1.6 \times 10^{-19} \times 500 \times 10^{-4}}$$

$$\therefore n_h = 3.75 \times 10^{24} \text{ holes/m}^3$$

**Answer**

Hence, density of electrons is,

$$n_e = \frac{n_i^2}{n_h} = \frac{(1.5 \times 10^{16})^2}{3.75 \times 10^{24}}$$

$$\therefore n_e = 6 \times 10^7 \text{ electrons/m}^3$$

**Answer**

**15) Find the density of impurity atoms that must be added to an intrinsic crystal in order to convert it into**

- i)  $10 \Omega \text{ cm } p\text{-type silicon}$
- ii)  $10 \Omega \text{ cm } n\text{-type silicon}$

**Also, find out concentration of minority carriers in each case.**

**For Si,  $\mu_e = 1350 \text{ cm}^2/\text{V} \cdot \text{sec}$ ,  $\mu_h = 480 \text{ cm}^2/\text{V} \cdot \text{sec}$ ,  $n_i = 1.5 \times 10^{10} / \text{cm}^3$**

**Solution**

$$n_i = 1.5 \times 10^{10} / \text{cm}^3 = 1.5 \times 10^{16} / \text{m}^3$$

$$\rho = 10 \Omega \text{cm} = 10 \times 10^{-2} \Omega \text{m}$$

$$\mu_e = 1350 \text{ cm}^2 / \text{V.sec} = 1350 \times 10^{-4} \text{ m}^2 / \text{V.sec}$$

$$\mu_h = 480 \text{ cm}^2 / \text{V.sec} = 480 \times 10^{-4} \text{ m}^2 / \text{V.sec}$$

$$N_d = ?, N_a = ?$$

$\Rightarrow$  For p-type

$$\text{Assuming } n_h = N_a$$

$$\sigma = n_h \cdot e \cdot \mu_h$$

$$\therefore \sigma = N_a \cdot e \cdot \mu_h$$

$$\therefore N_a = \frac{\sigma}{e \cdot \mu_h} = \frac{1}{\rho e \mu_h}$$

$$= \frac{1}{10 \times 10^{-2} \times 1.6 \times 10^{-19} \times 480 \times 10^{-4}}$$

$$\therefore N_a = 1.3 \times 10^{21} / \text{m}^3$$

**Answer**

Minority charge carriers,

$$n_e = \frac{n_i^2}{n_h}$$

$$\therefore n_e = \frac{(1.5 \times 10^{16})^2}{1.3 \times 10^{21}}$$

$$\therefore n_e = 1.72 \times 10^{11} \text{ electrons / m}^3$$

**Answer**

For N-type

$$\text{Assuming } n_e = N_d$$

$$\therefore \sigma = n_e \cdot e \cdot \mu_e$$

$$\therefore \sigma = N_d \cdot e \cdot \mu_e$$

$$\therefore N_d = \frac{\sigma}{e \mu_e} = \frac{1}{\rho e \mu_e}$$

$$\therefore N_d = \frac{1}{10 \times 10^{-2} \times 1.6 \times 10^{-19} \times 1350 \times 10^{-4}}$$

$$\therefore N_d = 4.62 \times 10^{20} / m^3$$

**Answer**

Minority charge carriers

$$n_h = \frac{n_i^2}{n_e}$$

$$\therefore n_h = \frac{(1.5 \times 10^{16})^2}{4.62 \times 10^{20}}$$

$$\therefore n_h = 4.86 \times 10^{11} \text{ holes/m}^3$$