

UNIT II

SEMICONDUCTING MATERIALS

2.1 INTRODUCTION

Semiconductors are materials whose electrical conductivities are between those of metals and insulators. Pure elemental silicon and germanium are intrinsic semiconducting materials. These elements which are in group IV-A of the periodic table, have the diamond structure with highly directional covalent bonds. Tetrahedral sp^3 hybrid bonding orbitals consisting of electron pairs binds the atoms together in the crystal lattice. In this structure each silicon or germanium atom contributes four valence electrons.

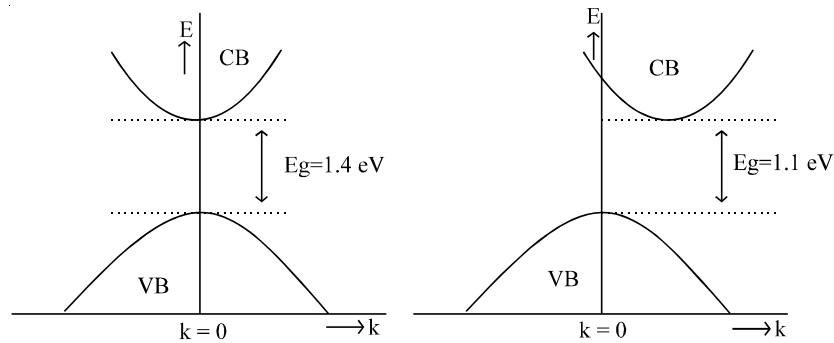
Properties of semiconductor

1. The resistivity of semiconductors lies between conducting and insulating materials. (i.e.,) 10^{-4} to $0.5 \text{ ohm} \cdot \text{metre}$.
2. At 0K they behave as insulators.
3. When the temperature is raised or when impurities are added, their conductivity increases.
4. They have negative temperature co-efficient of resistance.

The reason for the above property is, when the temperature is increased large number of charge carriers are produced due to breaking of covalent bonds and hence these electrons move freely and gives rise to conductivity.

5. In conductors the electrons are charge carriers and will take part in conduction but in semiconductor both electrons and holes are charge carriers and will take part in conduction. (Hole is produced by the vacancy of electrons at bond sites). Total conductivity, $\sigma = \sigma_e + \sigma_h$ Where, σ_e - conductivity due to electrons, σ_h - conductivity due to holes.

2.2. ELEMENTAL AND COMPOUND SEMICONDUCTORS



(a) Direct band gap (GaAs) (b) Indirect band gap (Si)

Fig. 2.1

Based on the composition of semiconductors they are classified as:

(i) Elemental Semiconductors

The elemental semiconductor is made of single element from the fourth column elements. Germanium and Silicon are the important examples for elemental semiconductors, these are also known as indirect band gap semiconductors. Here the recombination of an electron from the conduction band with a hole in the valence band takes place via traps. In this process, the phonons are emitted while recombination and they heat the lattice.

ii) Compound Semiconductors

The compound semi- conductors are made by combining the third and fifth column elements (or) second and sixth column elements. GaAs, InP are the important examples for compound semiconductors. They are also known as direct band gap semiconductors. Here the recombination of electron and hole takes place directly and its energy difference is emitted in the form of photons in the visible (or) Infrared range.

2.3. TYPES OF SEMICONDUCTOR

Based on the purity, semiconductors are classified into two

- (i) Intrinsic semiconductor
- (ii) Extrinsic semiconductor

Intrinsic semiconductor

A semiconductor in an extremely pure form is called as Intrinsic semiconductors. Examples: Germanium and Silicon.

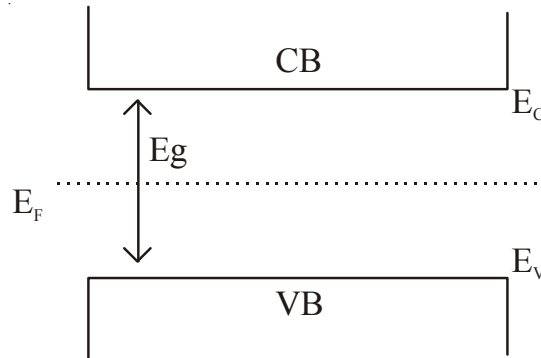


Fig. 2.2 Intrinsic semiconductor

In these semiconductors the electrons and holes can be created by the thermal agitation. As there are no impurities the number of free electrons must be equal to the number of holes.

At 0K the valence band is completely filled and the conduction bands are empty. The carrier concentration (i.e.,) electron density (or) hole density) exponentially with the increase in temperature.

A semiconductor in which holes and electrons are created only by thermal excitation across the energy gap is called an intrinsic semiconductor. A pure crystal of Si or Ge is an intrinsic semiconductor. The electrons reaching the conduction band due to thermal excitation is equal to the number of vacancies or holes in the valence band. That is, in an intrinsic semiconductor the concentration of holes and electrons must always be same. The Fermi level for an intrinsic semiconductor lies mid way in the forbidden gap. In intrinsic semiconductor, the conduction of charge carriers increases exponentially with temperature. Practically, intrinsic semiconductors are not useful ones because their electrical conductivity is smaller and it is not a constant.

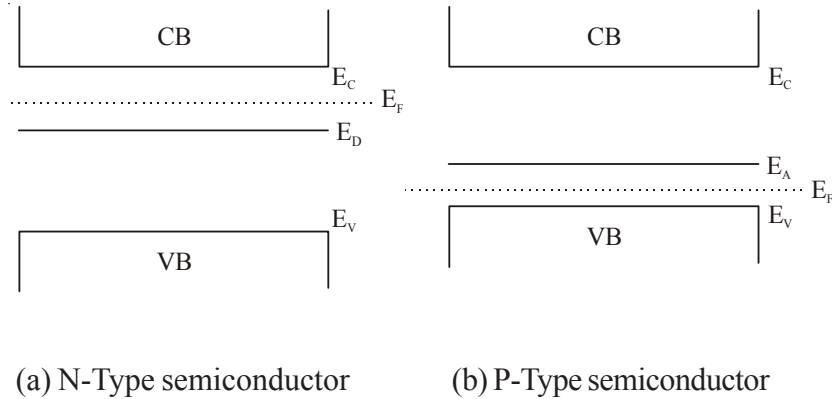


Fig. 2.3

Extrinsic semiconductor

A semiconductor in which charge carriers originate from impurity atoms is called an impure semiconductor or extrinsic semiconductor. In extrinsic semiconductors the conduction is mainly due to addition of impurities, which increases the conductivity of a semiconductor.

Based on the type of impurity added they are classified into

- i) N-type semiconductors
- ii) P-type semiconductors

Atoms like P, As and Sb have valency five. They can donate one electron to the semiconductor and the energy level of the fifth electron is called the donor level. Since these impurity atoms donate negative charges they are called N –type impurities and semiconductors doped with them are called N-type semiconductors. Excitation from donor level into the conduction band takes place much more rapidly than across the energy gap. The donor level is close to the conduction band and most of the donor level electrons are excited into the conduction band at room temperature and become the majority charge carriers. In a N –type semiconductor electrons are majority charge carriers.

Consider the impurities like Al, Ga or In in semiconductors. All have three electrons (valency 3) in outer shell. To complete their shell they require one more electron, that is supplied by the semiconductor atom like Si, there by creating a vacant electron site or

hole on the semiconductor atom. Since Al accepts an extra electron, the energy level of this is called acceptor level which lies just above the valence band. Hence Al, Ga and In are called acceptor impurities and the semiconductor is called as P-type semiconductor. The majority charge carriers in p-type semiconductor are holes. Unlike intrinsic semiconductors, the concentration of holes and electrons are not equal in extrinsic semiconductors.

2.4. INTRINSIC SEMICONDUCTORS

2.4.1. Carrier concentration in intrinsic semiconductors

We know, at 0K intrinsic semiconductor behaves as an insulator. But as temperature increases some electrons move from valence band to conduction band as shown in fig. 2.4. Therefore both electrons in conduction band and holes in valence band will contribute to electrical conductivity. Therefore, the carrier concentration (or) density of electrons (n_e) and holes (n_h) has to be calculated.

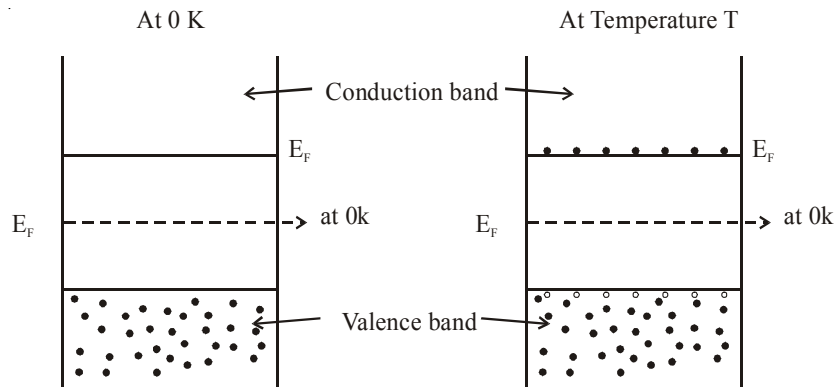


Fig. 2.4

Assume that electron in the conduction band is a free electron of mass m_e^* and the hole in the valence band behaves as a free particle of mass m_h^* . The electrons in the conduction band have energies lying from E_c to ∞ and holes in the valence band have energies from $-\infty$ to E_v as shown in fig. 2.4. Here E_c represents the energy of the bottom (or) lowest level of conduction band and E_v represents the energy of the top (or) the highest level of the valence band.

2.4.2. Density of Electrons in Conduction Band

$$\int_{E_c}^{\infty} f(E) g(E) dE \quad \rightarrow (2.1)$$

From Fermi-Dirac statistics we can write

$$Z(E) dE = 2 \cdot \frac{\pi}{4} \left(\frac{8m_e^*}{h^2} \right)^{1/2} E^{1/2} dE \quad \rightarrow (2.2)$$

Considering minimum energy of conduction band as E_c and the maximum energy can go upto ∞ we can write equation (2.2) as

$$Z(E) dE = \frac{\pi}{2} \left(\frac{8m_e^*}{h^2} \right)^{3/2} (E - E_c)^{1/2} dE \quad \rightarrow (2.3)$$

We know from Fermi function, probability of finding an electron in a given energy state is

$$f(E) = \frac{1}{1 + e^{(E - E_F)/K_B T}} \quad \rightarrow (2.4)$$

Substituting equation (2.4) and (2.3) in equation (2.1) we get density of electron in conduction band within the limits E_c to ∞ as

$$n_e = \frac{\pi}{2} \left(\frac{8m_e^*}{h^2} \right)^{3/2} \int_{E_c}^{\infty} \frac{(E - E_c)^{1/2}}{1 + e^{(E - E_F)/K_B T}} dE \quad \rightarrow (2.5)$$

Since to move an electron from valence band to conduction band the energy required is greater than 0.1 eV. (i.e.,) $E - E_F \gg 0.1 \text{ eV}$ (or) $(E - E_F) / K_B T \gg 1$

$$\text{(or)} \quad e^{(E - E_F)/K_B T} \gg 1$$

$$\therefore 1 + e^{(E - E_F)/K_B T} \approx e^{(E - E_F)/K_B T}$$

\therefore Equation (2.5) becomes

$$\left\{ \begin{array}{l} \int_{E_c}^{\infty} (E - E_c)^{1/2} \cdot e^{(E_F - E)/K_B T} dE \end{array} \right\} \rightarrow (2.6)$$

$$\text{or) } n_e = \frac{\pi}{2} \cdot \frac{8m_e^*}{h^2} \int_{E_c}^{\infty} (E - E_c)^{1/2} \cdot e^{(E_F - E)/K_B T} dE$$

Let us assume that $E - E_c = xK_B T$

$$(\text{or}) \quad E = E_c + xK_B T$$

Differencing we get $dE = K_B T \cdot dx$

Limits: When $E = E_c$: $x = 0$

\therefore When $E = \infty$; $x = \infty$

\therefore Limits are 0 to ∞

Equation (2.6) can be written as

$$n_e = \frac{\pi}{2} \cdot \frac{8m_e^*}{h^2} \int_{E_c}^{\infty} \frac{E - E_c}{e^{E - E_F / K_B T}} \cdot dE$$

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

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

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

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

$$\left[\text{Since } \int_0^\infty x^{1/2} e^{-x} dx = \frac{\sqrt{\pi}}{2} \right]$$

$$n_e = \frac{1}{4} \left\{ \frac{8\pi m_e^* K_B T}{h^2} \right\}^{3/2} e^{(E_F - E_g)/K_B T}$$

∴ Density of electrons in conduction band is

$$\left(\right) \quad (2.7)$$

2.4.3. Density of Holes in Valence Band

We know, $F(E)$ represents the probability of filled state. As the maximum probability will be 1, the probability of unfilled states will be $[1 - F(E)]$.

Example, If $F(E) = 0.2$ then $1 - F(E) = 0.8$

i.e., 20% chance of finding an electron in conduction band and 80% chance of finding a hole in valence band.

Let the maximum energy in valence band be E_v and the minimum energy be $-\infty$. Therefore density of holes in valence band n_h is given by

$$\int () \quad () \quad \rightarrow (2.8)$$

We know

$$n_h = \int_{-\infty}^{E_v} \left\{ \frac{8m_h^*}{h^2} \right\}^{3/2} (E_v - E)^{1/2} dE \quad \rightarrow (2.9)$$

$$1 - F(E) = 1 - \frac{1}{1 + e^{(E-E_F)/K_B T}}$$

$$= \frac{e^{(E-E_F)/K_B T}}{1 + e^{(E-E_F)/K_B T}}$$

Here

$$(or) \quad \frac{E - E_F}{K_B T} \ll 1 \quad \therefore e^{(E-E_F)/K_B T} \ll 1$$

$$(or) \quad 1 + e^{(E-E_F)/K_B T} \approx 1$$

$$\therefore 1 - F(E) = e^{(E-E_F)/K_B T} \quad \rightarrow (2.10)$$

substituting equation (2.10) and (2.9) in (2.8), we get

$$\left\{ \begin{array}{l} E - E_F \ll K_B T \\ \end{array} \right\} \quad n_h = \frac{\pi}{2} \cdot \frac{8m_h^*}{h^2} \int_{-\infty}^{E_v} (E_v - E)^{1/2} \cdot e^{(E-E_F)/K_B T} dE \quad \rightarrow (2.11)$$

Let us assume that $E_v - E = xK_B T$ (or) $E = E_v - xK_B T$

differentiating we get $dE = -K_B T dx$

Limits: When $E = -\infty$

We have

$$\therefore x = \infty \quad E_v - (-\infty) = xK_B T$$

When $E = E_v$; $x = 0$

\therefore Limits are ∞ to 0

\therefore Equation (2.11) becomes

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

To remove the negative sign, the limits can be interchanged

$$\therefore n_h = \frac{\pi}{2} \left\{ \frac{8m_h^*}{h^2} \right\}^{3/2} \int_0^\infty x^{1/2} (K_B T)^{3/2} e^{(E_v - E_F)/K_B T} \cdot e^{-x} \cdot dx$$

$$\text{or } n_h = \frac{\pi}{2} \frac{8m_h^* K_B T}{h^2} e^{(E_v - E_F)/K_B T} \int_0^\infty x^{1/2} \cdot e^{-x} \cdot dx$$

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

$$\left[\text{Since } \int_0^\infty x^{1/2} e^{-x} dx = \frac{\sqrt{\pi}}{2} \right]$$

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

\therefore Density of holes in valence band is

$$n_h = 2 \left\{ \frac{2\pi m_h^* K_B T}{h^2} \right\}^{3/2} e^{(E_v - E_F)/K_B T} \rightarrow (2.12)$$

2.4.4. Variation of Fermi energy level and carrier concentration with temperature in an intrinsic semiconductor

For an intrinsic semiconductor number of electrons (i.e.) electron density will be the same as that of number of holes (i.e.,) hole density.

$$\text{(i.e.,) } n_e = n_h$$

Equating equations (2.7) and (2.12), we can write

$$\left[m_e^* \right]^{3/2} e^{(E_F - E_c)/K_B T} = \left[m_h^* \right]^{3/2} e^{(E_v - E_F)/K_B T}$$

$$\begin{aligned} \left\{ \frac{m_h^*}{m_e^*} \right\}^{3/2} &= \frac{e^{(E_F - E_c)/K_B T}}{e^{(E_v - E_F)/K_B T}} \\ &= e^{(E_F - E_c - E_v + E_F)/K_B T} \end{aligned}$$

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

Taking log on both sides we have

$$\begin{aligned} 3/2 \log \left(\frac{m_h^*}{m_e^*} \right) &= \frac{[2E_F - (E_v + E_c)]}{K_B T} \\ 2E_F &= E_c + E_v + \frac{3}{2} K_B T \log \left(\frac{m_h^*}{m_e^*} \right) \\ E_F &= \frac{E_c + E_v}{2} + \frac{3}{4} K_B T \log \left(\frac{m_h^*}{m_e^*} \right) \quad \rightarrow (2.13) \end{aligned}$$

If $m_h^* = m_e^*$, then $\log \frac{m_h^*}{m_e^*} = 1$
 \therefore Equation (2.13) becomes

$$E_F = \frac{(E_c + E_v)}{2} \quad \rightarrow (2.14)$$

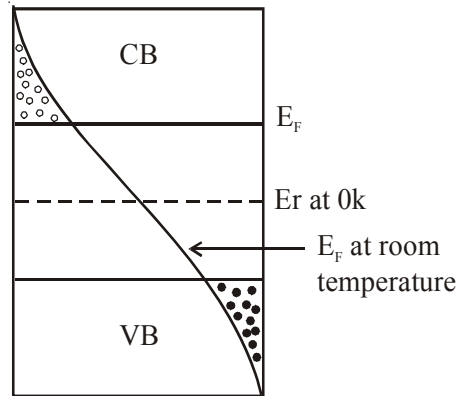


Fig. 2.5

i.e., the Fermi energy level lies in the midway between E_c and E_v as shown in fig. 2.5. (since at 0K, $K_B T = 0$)

But in actual case $m_h^* > m_e^*$ and the Fermi energy level slightly increases with the increase in temperature as shown in fig. 2.5.

2.4.5. Density of electrons and holes in terms of E_g

In terms of energy gap (E_g) where $E_g = E_c - E_v$ we can get the expression of n_e and n_h by substituting the value of E_F in terms of E_c and E_v .

Substituting equation (2.13) in (2.7) we get

$$n_e = 2 \left(\frac{2\pi m_e^* K_B T}{h^2} \right)^{3/2} \exp \left[\frac{\frac{E_c + E_v}{2} + \frac{3}{4} K_B T \log_e \left(\frac{m_h^*}{m_e^*} \right) - E_c}{K_B T} \right]$$

$$= 2 \left(\frac{2\pi K_B T}{h^2} \right) \left(m_e^* \right)^{3/2} \exp \left[\frac{2E_c + 2E_v + 3K_B T \log_e \left(\frac{m_h^*}{m_e^*} \right) - 4E_c}{4K_B T} \right]$$

$$= 2 \left[\frac{2\pi K_B T}{h^2} \right]^{3/2} [m_e^*]^{3/2} \exp \left[\frac{2 E_v - E_c}{4 K_B T} + \frac{3}{4} \log_e \left(\frac{m_h^*}{m_e^*} \right) \right]$$

Since $E_g = E_c - E_v$, we can write

$$n_e = 2 \left[\frac{2\pi K_B T}{h^2} \right]^{3/2} [m_e^*]^{3/2} \exp \left[\frac{-E_g}{2 K_B T} + \log_e \left(\frac{m_h^*}{m_e^*} \right)^{3/4} \right]$$

$$\text{or } n_e = 2 \left[\frac{2\pi K_B T}{h^2} \right]^{3/2} [m_e^*]^{3/2} \frac{[m_h^*]^{3/4}}{[m_e^*]^{3/4}} e^{-E_g/2 K_B T}$$

$$\text{or } n_e = 2 \left[\frac{2\pi K_B T}{h^2} \right]^{3/2} [m_e^*]^{3/4} [m_h^*]^{3/4} e^{-E_g/2 K_B T}$$

$$n_e = 2 \left[\frac{2\pi K_B T}{h^2} \right]^{3/2} [m_e^* m_h^*]^{3/4} e^{-E_g/2 K_B T} \rightarrow (2.15)$$

Similarly by substituting equation (2.13) in (2.12) we get

$$n_h = 2 \left\{ \frac{2\pi K_B T}{h^2} \right\}^{3/2} [m_h^* m_e^*]^{3/4} e^{-E_g/2 K_B T} \rightarrow (2.16)$$

Thus, it is found that $n_e = n_h = n_i$ where n_i is the intrinsic carrier concentraion.

Results

- * In an intrinsic semiconductor the density of electrons in conduction band is equal to the density of holes in valence band (i.e.,) $n_e = n_h$
- * n_e and n_h increases exponentially as the temperature increases.

2.4.6. Conductivity of an intrinsic semiconductor

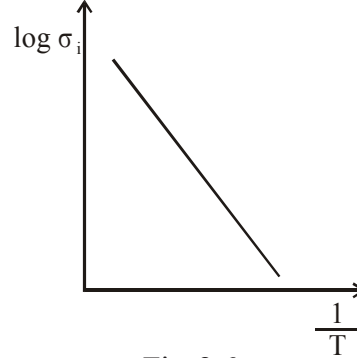


Fig. 2.6

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

$$= 2 \left[\frac{2\pi k_B T}{h^2} \right]^{\frac{3}{2}} \left[m_e^* m_h^* \right]^{\frac{3}{4}} \exp \left[\frac{-E_g}{2k_B T} \right] (\mu_e + \mu_h) \quad \rightarrow (2.17)$$

In eqn. (2.17) μ_e and μ_h are proportional to $T^{\frac{3}{2}}$. Therefore the co-efficient of

$\exp \left[\frac{-E_g}{2k_B T} \right]$ is a constant

$$\therefore \sigma_i = \sigma_0 \exp \left[\frac{-E_g}{2k_B T} \right] \quad \rightarrow (2.18)$$

Fig. (2.16) shows the variation of $\log \sigma_i$ with $\frac{1}{T}$. From this graph we can understand that conductivity increases with temperature.

2.4.7. Energy gap in intrinsic semiconductor

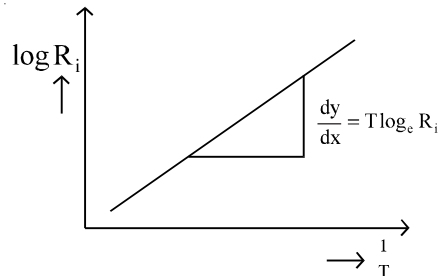


Fig. 2.7

The intrinsic conductivity, $\sigma_i = \sigma_0 \exp \left[\frac{-E_g}{2k_B T} \right]$

\therefore The resistivity of an intrinsic semiconductor,

$$\rho_i = \frac{1}{\sigma_0} \exp \left[\frac{E_g}{2k_B T} \right]$$

$$\text{i.e., } \frac{R_i a}{L} = \frac{1}{\sigma_0} \exp \left[\frac{E_g}{2k_B T} \right]$$

where R_i - resistance of the semiconductor

a - area of cross-section and L - length

$$\therefore R_i = R_0 \exp \left[\frac{E_g}{2k_B T} \right] \quad \left[\because \frac{L}{a\sigma_0} = R_0, \text{ constant} \right]$$

Taking natural logarithm on both sides,

$$\log_e R_i = \log R_0 + \frac{E_g}{2k_B T}$$

The resistances of a semiconductor are measured at various temperatures using Carey-Foster bridge. A graph is drawn connecting $1/T$ and $\log_e R_i$. From fig. (2.7),

$$\text{slope} = \frac{E_g}{2k_B}$$

$$\therefore E_g = 2k_B \times \text{slope}$$

Thus the energy gap of an intrinsic semiconductor is determined

2.5 EXTRINSIC SEMICONDUCTORS

2.5.1. Carrier concentration in N-type semiconductor

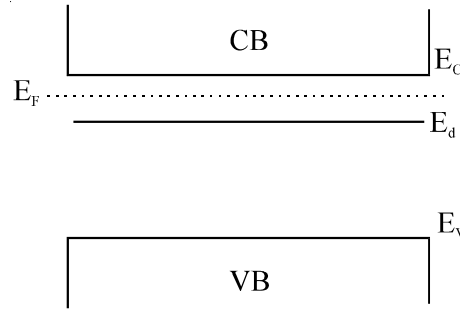


Fig. 2.8

Let N_d be the number of donor levels per unit volume of energy E_d lying below the conduction band. At low temperatures small fraction of donors will be ionized and practically all donor levels will be filled.

When $E_C - E_F > 4k_B T$, the density of electrons in the conduction band will be,

$$n = 2 \left[\frac{2\pi m_e^* k_B T}{h^2} \right]^{\frac{3}{2}} \exp \left[\frac{E_F - E_C}{k_B T} \right] \quad \rightarrow (2.19)$$

If we assume $E_F - E_d \gg 4k_B T$, (above the donor level), then the density of empty donor level is,

$$N_d(1 - F(E_d)) = N_d \exp \left[\frac{E_d - E_F}{k_B T} \right] \quad \rightarrow (2.20)$$

At very low temperatures, no electrons are excited from the valence band into the conduction band. Therefore the density of empty donor levels should be the same as the density of electrons in the conduction band.

$$2 \left[\frac{2\pi m_e^* k_B T}{h^2} \right]^{\frac{3}{2}} \exp \left[\frac{E_F - E_C}{k_B T} \right] = N_d \exp \left[\frac{E_d - E_F}{k_B T} \right]$$

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

Taking natural logarithm on both sides, we get,

$$\begin{aligned} \log_e 2 \left(\frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2} + \frac{E_F - E_C}{k_B T} &= \log_e N_d + \frac{E_d - E_F}{k_B T} \\ \frac{2E_F - E_C - E_d}{k_B T} &= \log_e \frac{N_d}{2} \left(\frac{2\pi m_e^* k_B T}{h^2} \right)^{-3/2} \\ \therefore E_F &= \frac{E_C + E_d}{2} + \frac{k_B T}{2} \log_e \frac{N_d}{2} \left(\frac{2\pi m_e^* k_B T}{h^2} \right)^{-3/2} \end{aligned}$$

→ (2.20)

At $T = 0$ K,

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

i.e., At absolute zero, the Fermi level lies exactly half way between the donor level and bottom of the conduction band. As the temperature increases, the Fermi level falls below the donor level and it approaches the center of forbidden gap which makes the substance an intrinsic semiconductor. This gives a limit on the operating temperature of a semiconducting device. Fig. (2.9) shows the variation of Fermi level with temperature in n-type and p-type semiconductors. The effect of donor and acceptor concentrations also is shown.

Substituting the value of E_F from eqn. (2.20) in eqn. (2.19), the electron density in the conduction band can be obtained. Consider the term,

$$\begin{aligned}
\exp \frac{E_F - E_C}{k_B T} &= \exp \left[\left(\frac{E_C + E_d}{2k_B T} - \frac{E_C}{k_B T} \right) + \frac{1}{2} \log_e \frac{N_d}{2} \left(\frac{2\pi m_e^* k_B T}{h^2} \right)^{-\frac{3}{2}} \right] \\
&= \exp \left[\frac{E_d - E_C}{2k_B T} \right] \exp \left[\log_e \left[\frac{N_d}{2} \right]^{\frac{1}{2}} \left[\frac{2\pi m_e^* k_B T}{h^2} \right]^{-\frac{3}{4}} \right] \\
&= \left[\frac{N_d}{2} \right]^{\frac{1}{2}} \left[\frac{2\pi m_e^* k_B T}{h^2} \right]^{-\frac{3}{4}} \exp \left[\frac{E_d - E_C}{2k_B T} \right]
\end{aligned}$$

∴ The electron density in the conduction band,

$$\begin{aligned}
n &= 2 \left[\frac{2\pi m_e^* k_B T}{h^2} \right]^{\frac{3}{2}} \left[\frac{N_d}{2} \right]^{\frac{1}{2}} \left[\frac{2\pi m_e^* k_B T}{h^2} \right]^{-\frac{3}{4}} \exp \left[\frac{E_d - E_C}{2k_B T} \right] \\
\text{i.e., } n &= \sqrt{2N_d} \left[\frac{2\pi m_e^* k_B T}{h^2} \right]^{\frac{3}{4}} \exp \left[\frac{E_d - E_C}{2k_B T} \right] \quad \rightarrow (2.21)
\end{aligned}$$

Eqn. (2.21) shows that the density of electrons in the conduction band is proportional to the square root of the donor concentration.

Similarly the density of holes in the p-type semiconductor can be derived as,

$$p = \sqrt{2N_a} \left[\frac{2\pi m_h^* k_B T}{h^2} \right]^{\frac{3}{4}} \exp \left[\frac{E_V - E_A}{2k_B T} \right] \quad \rightarrow (2.22)$$

2.5.2. Variation of Fermi level and carrier concentration with temperature and impurities in 'n'-Type semiconductor

When the temperature is increased some electrons in E_d level may be shifted to conduction band and hence some vacant sites will be created in E_d levels. Therefore the Fermi level shifts down to separate that empty levels and the filled valence band level as shown in fig. 2.10, for the doping level of $N_d = 10^{21}$ atoms / m^3

From the fig 2.10 it can be seen that for the same temperature, if the impurity atoms i.e., doping level is increased ($N_d = 10^{24}$ atoms/ m^3), the electron concentration increases and hence the Fermi level increases.

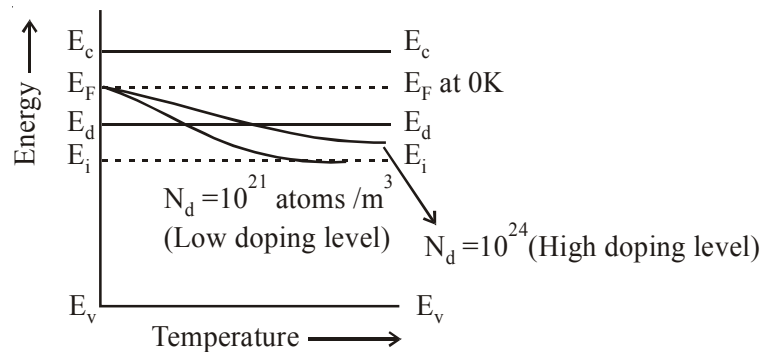


Fig. 2.9

2.5.3. P-type semiconductor

When a small amount of trivalent impurity is added to a pure semiconductor, it becomes P-type semiconductor.

The trivalent impurity provides a large number of holes in the semiconductor.

Typical examples of trivalent impurities are gallium (Atomic no. 31) and indium (Atomic no. 49). Such impurities are known as acceptor impurities because the holes they create can accept electrons.

To a pure semiconductor (germanium) having 4 valence electrons, if a trivalent impurity (boron) having '3' valence impurity is added, then 3 valence electrons of trivalent impurity form a covalent bond with three valence electrons of germanium. The fourth electron is unable to form a covalent bond. The incomplete covalent bond being short of one electron (missing electron) is called a hole.

Every trivalent atom contributes one hole in addition to thermally generated electron-hole pairs. Therefore, the number of holes is more than the number of electrons (fig. 2.10 (a)).

The addition of trivalent impurity creates a large number of holes (positive charge carries) in the semiconductor and hence called P-type semiconductor where p stands for positive type. Moreover, holes are majority charge carries and electrons are minority charge carries.

In this case, the allowable energy level (acceptor energy level) is created just above the valence band (fig. 2.10 (b)). A very small amount of energy is needed for an electron to enter the acceptor energy level. Thus a number of holes is generated in the valence band,

In other words, a large number of positive charge carries are created.

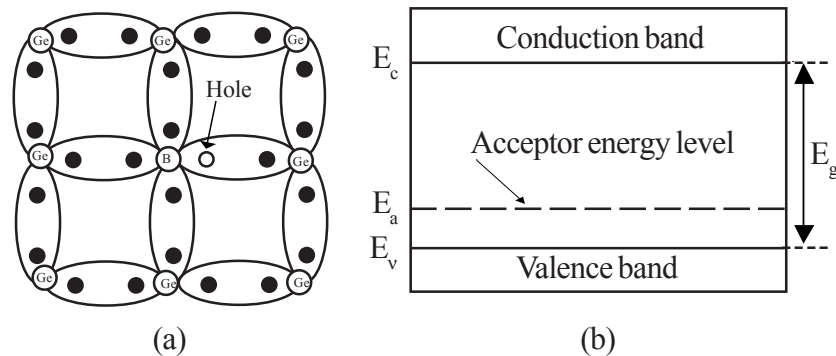


Fig. 2.10 P-type semiconductor : (a) crystal structure
(b) energy band diagram

2.5.4. CONCENTRATION OF HOLES IN THE VALENCE BAND P-TYPE SEMICONDUCTOR (Derivation)

In p-type semiconductor, the acceptor level is just above the valence band (fig. 2.11). Let E_a represent the energy of the acceptor level and N_a denote the number of acceptor atoms per unit volume.

Density of holes per unit volume in the valence band is given by

$$P = 2 \left[\frac{2\pi m^* kT}{h^2} \right]^{3/2} e^{(E_v - E_F)/kT}$$

where E_F is Fermi energy level; E_v is the energy corresponding to the top of valence band.

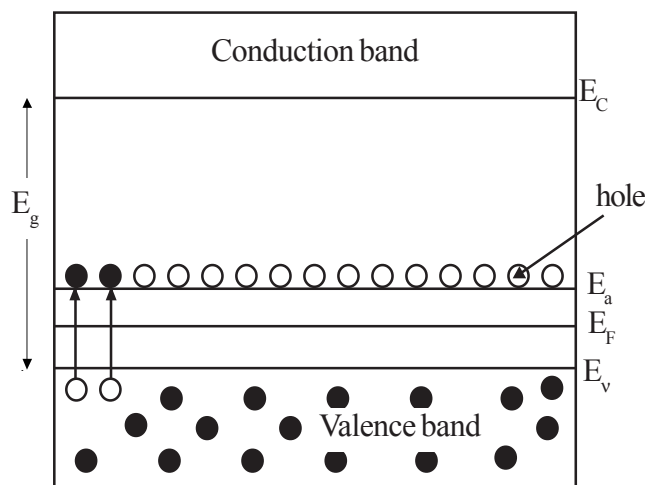


Fig. 2.11 Energy band diagram for P-type semiconductor

Density of ionised acceptors

$$= N_a F(E_a) = \frac{N_a}{1 + e^{(E_a - E_F)/kT}} \quad \text{----(2)}$$

Since $E_a - E_F \gg kT$, $e^{(E_a - E_F)/kT}$ may be a large quantity, and thus '1' can be neglected from the denominator of R.H.S. of equation (2).

$$\text{Density of ionised acceptors} = N_a e^{(E_F - E_a)/kT} \quad \text{--- (3)}$$

At equilibrium

Density of holes in the valence band = Density of ionised acceptors

$$2 \left[\frac{2\pi m^* kT}{h^2} \right]^{3/2} e^{\frac{(E_v - E_F)kT}{h^2}} = n_a e^{\frac{(E_F - E_a)kT}{h^2}} \quad \text{---- (4)}$$

Taking log on both sides of equation (4), we have

$$\log_e \left[2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{3/2} \right] + \frac{E_v - E_F}{kT} = \log N_a + \frac{E_F - E_v}{kT}$$

Rearranging, we get

$$\frac{E_F - E_v - E_v - E_F}{kT} = \log N_a \log \left[2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{3/2} \right]$$

$$\text{or} \quad \frac{2E_F - (E_a - E_v)}{kT} = - \log \left[\frac{N_a}{2 \left[\frac{2\pi m^* kT}{h^2} \right]^{3/2}} \right]$$

$$\text{or} \quad 2E_F - (E_a - E_v) - kT \log \left[\frac{N_a}{2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{3/2}} \right] \quad \text{----(5)}$$

$$\therefore E_F = \frac{E_a + E_v}{2} - \frac{kT}{2} \log \left[\frac{N_a}{2 \left[\frac{2\pi m^*}{h^2} \right]^{3/2}} \right] \quad \text{---- (6)}$$

Substituting the expression of E_F from (6) in (1), we get

$$\begin{aligned}
 p &= 2 \left[\frac{2\pi m_h^*}{h^2} \right]^{3/2} \exp \left\{ \frac{\frac{E_v + E_a}{2} - \frac{kT}{2}}{kT} \left[\frac{Na}{2 \left[\frac{2\pi m_h^*}{h^2} \right]^{3/2}} \right] \right\} \\
 p &= 2 \left[\frac{2\pi m_h^*}{h^2} \right]^{3/2} \exp \left[\frac{2E_v - E_v - E_a}{2kT} \right] \log \left[\frac{Na}{2 \left[\frac{2\pi m_h^*}{h^2} \right]^{3/2}} \right] \\
 p &= 2 \left[\frac{2\pi m_h^*}{h^2} \right]^{3/2} \frac{\left(\frac{Na}{2} \right)^{1/2}}{2 \left[\frac{2\pi m_h^*}{h^2} \right]^{3/4}} e^{(E_v - E_a)/2kT} \\
 \therefore p &= (2N_a)^{1/2} \left[\frac{2\pi m_h^*}{h^2} \right]^{3/2} e^{(E_v - E_a)/2kT} \quad \text{----- (7)}
 \end{aligned}$$

If we put $E_a - E_v = \Delta E$, equation (7) becomes

The concentration of hole in a p-type semiconductor is given by

$$\boxed{\therefore p = (2N_a)^{1/2} \left[\frac{2\pi m_h^*}{h^2} \right]^{3/2} e^{-\Delta E/2kT}} \quad \text{---- (8)}$$

It is clear from equation (8) that the density of holes in the valence band is proportional to the square root of acceptor concentration.

2.5.5. Carrier Concentration in p-type semiconductor

When the temperature is increased, some of the electrons in the valence band will go to acceptor energy levels by breaking up the covalent bonds and hence the Fermi level is shifted in upward direction for doping level of $N_d = 10^{21}$ atoms/m³ as shown in figure 2.12.

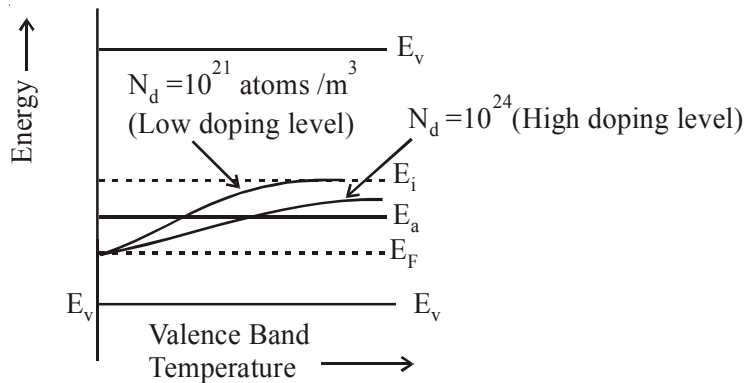


Fig. 2.12

From the fig. 2.12 it can be seen that for the same temperature, if the impurity atoms (i.e.,) doping level is increased say $N_a = 10^{24}$ atoms/m³ the hole concentration increases and hence the Fermi level decreases.

Therefore at low temperature the Fermi energy level may be increased upto the level of intrinsic energy level (E_i)

2.6. HALL EFFECT

Consider a specimen in the form of rectangular cross-section carrying a current of density J in the x -direction. If a constant magnetic field B is applied along the z -direction, it is found that an emf develops in a direction perpendicular to both of these. i.e., along the y -direction. This voltage is called the **Hall voltage** and the effect is **Hall effect**.

The Hall effect refers to the production of transeverse electric field when a current carrying conductor is placed right angle to the applied magnetic field. It gives the information of the sign of the charge carrier.

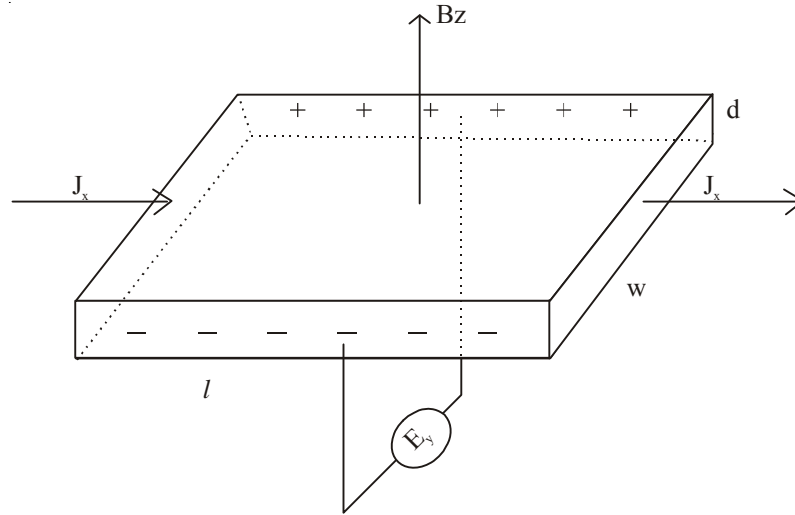


Fig. 2.13 Hall effect (n-type semiconductor)

The magnetic induction B exerts a force on the charged particles carrying current and displacing them in the y -direction. This sets up a non-uniform charge density, which gives rise to an electric field in the y -direction. In equilibrium the force due to this field must just balance the force due to the magnetic field.

$$\text{i.e., } Ee = -e(v_d \times B)$$

$$\therefore E = -v_d \times B$$

$$= -\left[\frac{J}{ne}\right] \times B$$

where $J = ne v_d$ - is the current density

n - number of charge carriers per unit volume

$$\text{Now, } E = -R_H (J \times B)$$

where R_H is the **Hall coefficient**

$$R_H = -\frac{1}{n|e|} \quad (\text{or}) \quad R_H = \frac{E_y}{J_x B_z} \rightarrow (2.23)$$

The negative sign in eqn. (2.23) implies that we would expect R_H to be negative for electrons of negative charge.

Generally, when relaxation time is dependent on velocity, then,

$$R_H = -\frac{3\pi}{8} \frac{1}{n|e|}$$

Experiment

In measuring the voltage due to the Hall effect, a rectangular strip whose thickness and width are small compared with the length is used as shown in fig. (2.11). The x- axis is taken along the strip (length) and y- axis along the width. Hall effect is observed by measuring the transverse voltage set up across the strip. This is the external voltage required to make the current flow entirely in x- direction (fig. 2.14 (a) and 2.14 (b)).

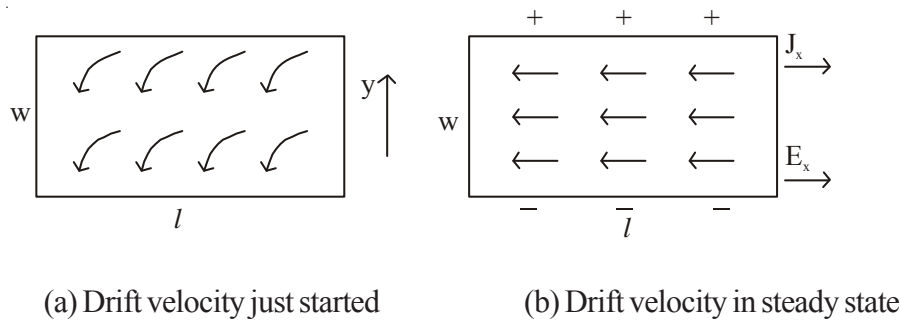


Fig. 2.14 Section perpendicular to z-axis

Results :

1. In an intrinsic semiconductor, the Hall co-efficient will not vanish, even though there are equal number of holes and electrons.

The general expression for intrinsic semiconductor

$$R_H = -\frac{1}{n_i|e|} \left[\frac{b-1}{b+1} \right]$$

where $b = \frac{\mu_e}{\mu_h}$ is the mobility ratio. Since $\mu_e > \mu_h$; $b > 1$

Thus the electron conduction predominates in the intrinsic semiconductor.

2. Most of the monovalent metals have negative Hall co-efficient. But for elements like Zn and Cd, R_H is positive. According to band theory of solids, a material with nearly filled valence band can give rise to negative electron mass conduction or hole conduction. Due to the possible hole conduction Zn and Cd have positive R_H .

Applications of Hall effect

1. Determination of semiconductor type

For a n-type semiconductor, Hall coefficient is negative, whereas for a p-type semiconductor it is positive. Thus, the sign of the Hall coefficient is used to determine whether a given semiconductor is n-type or p-type.

2. Calculation of carrier concentration

By measuring hall coefficient R_H , carrier concentration can be obtained from

$$n = \frac{1}{eR_H}$$

3. Determination of mobility

We know that electrical conductivity, $\sigma_e = ne\mu_e$.

$$\text{Hence, } \mu_e = \frac{1}{ne} \sigma_e$$

$$\text{or } \mu_e = \sigma_e R_H$$

Thus, by measuring electrical conductivity and Hall coefficient of a sample, the mobility of charge carries can be calculated.

4. Magnetic field meter

Hall voltage V_H for a given current is proportional to B . Hence V_H measures the magnetic field B .

5. Hall effect multiplier

This instrument can give an output proportional to the product of two signals. Thus, if current I is made proportional to one input and if B is proportional to the second input, then hall voltage V_H is proportional to the product of two inputs.

Importance of Hall effect

The study of Hall effect gives the following important information

- The sign of current carrying charges.
- The number of charge carries per unit volume.
- The mobility of charge carries.
- Type of material ie., whether a material is a metal, semiconductor or an insulator.

SOLVED PROBLEMS:

- 1. The intrinsic resistivity of germanium at 300 K is 0.47 ohm. m. What is the intrinsic carrier concentration when the electron and hole mobilities in Ge at 300K are 0.39 m²/V.s and 0.19 m²/V.s?**

Solution:

The intrinsic conductivity, $\sigma_i = (n_i e \mu_e + \mu_p) = \frac{1}{\rho_i}$

$$n_i = \frac{1}{\rho_i e (\mu_e + \mu_p)}$$

$$= \frac{1}{0.47 \times 1.602 \times 10^{-19} \times (0.39 + 0.19)}$$

$$= 2.29 \times 10^{-19} \text{ m}^{-3}$$

The intrinsic carrier concentration for Ge at 300K is $2.3 \times 10^{19} \text{ m}^{-3}$.

- 2. What is the donor concentration in n-type germanium when its resistivity is 0.01 ohm.m at 300K? The mobility of electron in germanium is 0.39 m²/V.s.**

Solution :

For n-type semiconductor $\sigma = ne\mu_e = \frac{1}{\rho}$

$$n = \frac{1}{\rho e \mu_e}$$

$$= \frac{1}{0.01 \times 1.602 \times 10^{-19} \times 0.39} = 1.6 \times 10^{21} \text{ m}^{-3}$$

Concentration of electrons in n-type Ge, $1.6 \times 10^{21} \text{ m}^{-3}$

At room temperature the electron concentration in the n-type semiconductor is equal to the donor concentration.

\therefore The donor concentration in n-type germanium = $1.6 \times 10^{21} \text{ m}^{-3}$

3. Calculate the intrinsic carrier density, conductivity and resistivity for Ge at 300K. Suppose if one boron atom for every 10^5 germanium atoms is added, what is the new resistivity and conductivity of germanium.

$$(E_g = 0.7 \text{ eV}; m_e^* = m_e)$$

Solution:

- (i) The intrinsic carrier concentration,

$$\begin{aligned} n_i &= 2 \left(\frac{2\pi m_e^* k_B T}{h^2} \right)^{\frac{3}{2}} \exp \left(-\frac{E_g}{2k_B T} \right) \\ &= 2 \left[\frac{2 \times 3.14 \times 9.1 \times 10^{-31} \times 1.38 \times 10^{-23} \times 300}{6.626 \times 10^{-34}^2} \right] \exp \left(-\frac{0.7 \times 1.602 \times 10^{-19}}{2 \times 1.38 \times 10^{-23} \times 300} \right) \\ &= 2.1 \times 10^{19} \text{ m}^{-3} \end{aligned}$$

- (ii) The intrinsic conductivity,

$$\begin{aligned} \sigma_i &= q_i e (\mu_n + \mu_p) \\ &= 2.1 \times 10^{19} \times 1.602 \times 10^{-19} \times (0.39 + 0.19) \\ &= 2.016 \text{ ohm}^{-1} \text{ m}^{-1} \end{aligned}$$

- (iii) Intrinsic resistivity,

$$\begin{aligned} \rho_i &= \frac{1}{\sigma_i} = \frac{1}{2.016} \\ &= 0.496 \text{ ohm.m} \end{aligned}$$

(iv) Number of Ge atoms per unit volume

$$\begin{aligned} &= \frac{\text{avagadro number} \times \text{density}}{\text{atomic weight}} \\ &= \frac{6.023 \times 10^{26} \times 5400}{72.5} \\ &= 4.5 \times 10^{28} \text{ m}^{-3} \end{aligned}$$

∴ Number of boron atoms in Ge per unit volume is $4.5 \times 10^{23} \text{ m}^{-3}$

(v) Conductivity of p-type Ge,

$$\begin{aligned} \sigma &= p e \mu_p \\ &= 4.5 \times 10^{23} \times 1.602 \times 10^{-19} \times 0.19 \\ &= 1.44 \times 10^4 \text{ ohm}^{-1} \cdot \text{m}^{-1} \end{aligned}$$

(vi) Resistivity of p-type Ge,

$$\begin{aligned} &= \frac{1}{\sigma} = \frac{1}{1.44 \times 10^4} \\ &= 0.694 \times 10^{-4} \text{ ohm} \cdot \text{m} \end{aligned}$$

4. A n-type semiconductor has Hall co-efficient $3.66 \times 10^{-4} \text{ m}^3 / \text{Coulomb}$. The conductivity of the specimen is $112 \text{ ohm}^{-1} \cdot \text{m}^{-1}$. Calculate the carrier density and electron mobility at room temperature.

Solution:

(i) The Hall co-efficient,

$$R_H = \frac{1}{ne}$$

$$n = \frac{1}{R_H \cdot e}$$

$$= \frac{1}{3.66 \times 10^{-4} \times 1.602 \times 10^{-19}}$$

$$= 1.705 \times 10^{22} \text{ m}^{-3}$$

The carrier concentration is $1.705 \times 10^{22} \text{ m}^{-3}$

(ii) The conductivity of a n- type semiconductor,

$$\sigma = ne\mu_n$$

$$\mu_n = \frac{\sigma}{ne}$$

$$= \frac{112}{1.7055 \times 10^{22} \times 10^{-19}} = 0.041 \text{ m}^2 / \text{V.s}$$

Electron mobility is $\mu_n = 0.041 \text{ m}^2 / \text{V.s}$

- 5. Find the conductivity of intrinsic Si at 300K. For silicon $n_i = 1.5 \times 10^{16} \text{ m}^{-3}$, $\mu_n = 0.13 \text{ m}^2 / \text{V.s}$, $\mu_p = 0.05 \text{ m}^2 / \text{V.s}$. The number of silicon atoms per unit volume is $5 \times 10^{28} \text{ m}^{-3}$. Also find the resultant conductivity if donor or acceptor impurity is added in the ratio $1:10^8$**

Solution:

The intrinsic conductivity of Si,

$$\begin{aligned}\sigma_i &= n_i e \mu_n + \mu_p \\ &= 1.5 \times 10^{16} \times 1.602 \times 10^{-19} \times 0.18 \\ &= 4.325 \times 10^{-4} \text{ ohm.m}^{-1}\end{aligned}$$

Number of silicon atoms per unit volume is 5×10^{28}

For n - type:

The donor concentration $= 5 \times 10^{20}$

$$\begin{aligned}\therefore \text{conductivity} &= n e \mu_n \\ &= 5 \times 10^{20} \times 1.602 \times 10^{-19} \times 0.13 \\ &= 10.4 \text{ ohm}^{-1} \cdot \text{m}^{-1}\end{aligned}$$

For p- type:

The acceptor concentration $= 5 \times 10^{20} \text{ m}^{-3}$

$$\begin{aligned}\therefore \text{conductivity} &= p e \mu_p \\ &= 5 \times 10^{20} \times 1.602 \times 10^{-19} \times 0.05 \\ &= 4 \text{ ohm}^{-1} \text{ m}^{-1}\end{aligned}$$

6. The electrical conductivity of Ge at 20°C is $2 \text{ ohm}^{-1} \text{ m}^{-1}$. What is its conductivity at 40°C ? Energy gap for Ge = 0.7 eV.

Solution:

$$\begin{aligned}\sigma_1 &= A \exp \left(-\frac{E_g}{2k_B T_1} \right) \\ \sigma_2 &= A \exp \left(-\frac{E_g}{2k_B T_2} \right) \\ \frac{\sigma_2}{\sigma_1} &= \exp \left(\frac{E_g}{2k_B} \left(\frac{1}{T_1} - \frac{1}{T_2} \right) \right)\end{aligned}$$

$$\begin{aligned}\log_e \frac{\sigma_2}{\sigma_1} &= \frac{E_g}{2k_B} \left(\frac{1}{T_1} - \frac{1}{T_2} \right) \\ &= \frac{0.7 \times 1.602 \times 10^{-19}}{2 \times 1.38 \times 10^{-23}} \left(\frac{1}{293} - \frac{1}{313} \right) \\ &= 0.886 \\ \sigma_2 &= 2 \times \exp(0.886) \\ &= 4.85 \text{ ohm}^{-1} \text{ m}^{-1}\end{aligned}$$

Conductivity of Germanium at 40° C is 4.85 ohm⁻¹ m⁻¹

- 7. The electrical conductivity and electron mobility of aluminium are 3.8 × 10⁷ ohm⁻¹ m⁻¹ and 0.0012 m²/V.s. Calculate the Hall voltage for an Al specimen with 15 mm thickness for a current of 25 A and a magnetic field of 0.6 Tesla.**

Solution:

- (i) The Hall co-efficient,

$$\begin{aligned}R_H &= \frac{1}{n|e|} \\ \text{But, } \sigma &= ne\mu_n \quad (\text{or}) \quad ne = \frac{\sigma}{\mu_n}\end{aligned}$$

$$R_H = \frac{\mu_n}{\sigma}$$

$$= \frac{0.0012}{3.8 \times 10^7}$$

$$= 3.15 \times 10^{-11} \text{ m}^3 / \text{Coulomb.}$$

- (ii) The Hall voltage,

$$\begin{aligned}V &= \frac{R_H \cdot I_x \cdot B_z}{d} \\ &= \frac{3.15 \times 10^{-11} \times 25 \times 0.6}{15 \times 10^{-3}} \\ &= 3.15 \times 10^{-8} \text{ V}\end{aligned}$$

EXERCISES

1. A n-type semiconductor with electron concentration 10^{21} m^{-3} has resistivity 0.1 ohm.m . Determine the drift velocity of electrons under a potential gradient of 150 V/m .
2. The gallium arsenide compound semiconductor possesses an intrinsic conductivity of $10^{-6} \text{ ohm}^{-1} \text{ m}^{-1}$, at 20°C . Determine the intrinsic carrier concentration. (For GaAs, $\mu_n = 0.88 \text{ m}^2/\text{V.s}$ and $\mu_p = 0.04 \text{ m}^2/\text{V.s}$)
3. The resistivity of germanium at 20°C is 0.5 ohm.m . Calculate its resistivity at 50°C .
4. Silicon with conductivity $200 \text{ ohm}^{-1} \text{ m}^{-1}$ has to be formed by adding aluminium as impurity. Determine the concentration of aluminium atoms required per m^3 of silicon. (For silicon $\mu_p = 0.0425 \text{ m}^2/\text{V.s}$)
5. A p-type silicon semiconductor contains 10^{22} aluminium atoms per m^3 . At what temperature the intrinsic conductivity of silicon will be equal to the maximum extrinsic conductivity?
(For Si, $\sigma_{\text{intrinsic}} = 5 \times 10^{-4} \text{ ohm}^{-1} \text{ m}^{-1}$; $E_g = 1.1 \text{ eV}$)
6. The drift velocity of electrons in a n-type semiconductor is 149 m/sec . under a potential gradient of 150 V/m . Determine the carrier concentration if the resistivity is 0.8 ohm.m .
7. Silicon has a density of 2330 kg/m^3 . (i) Determine the number of silicon atoms per m^3 . (ii) Phosphorous is added to silicon to make it a n-type semiconductor with conductivity $200 \text{ ohm}^{-1} \text{ m}^{-1}$. Determine the donor concentration in silicon. (For silicon $\mu_n = 0.19 \text{ m}^2/\text{V.s}$)
8. Determine the temperature at which the resistivity of Si is 50 percent of its value at 0°C .
9. An intrinsic semiconductor has a conductivity of $390 \text{ ohm}^{-1} \text{ m}^{-1}$ at 5°C and $1010 \text{ ohm}^{-1} \text{ m}^{-1}$ at 25°C . (i) Estimate the energy gap. (ii) Determine the conductivity at 15°C .
10. The Hall coefficient of certain silicon specimen was found to be $-7.35 \times 10^{-5} \text{ m}^3 \text{ C}^{-1}$ from 100 to 400 K. Determine the nature of the semiconductor. If the conductivity was found to be $200 \text{ ohm}^{-1} \text{ m}^{-1}$, calculate the density and mobility of the charge carrier.

PART -A QUESTIONS AND ANSWERS

- 1. Write an expression for the concentration of electrons in the conduction band of an intrinsic semiconductor.**

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

here $m_e^* \rightarrow$ effective mass of electron

$E_F \rightarrow$ Fermi energy level

$E_c \rightarrow$ Energy corresponds to conduction band

$T \rightarrow$ Absolute temperature

- 2. What are the advantages of compound semiconductors over elemental semiconductors:**

| Compound semiconductors | Elemental semiconductors |
|--|--------------------------------------|
| 1. Electron mobilities are higher | 1. Electron mobilities are smaller |
| 2. The values of band gaps can be varied by mixing different binary compounds. | 2. The values of band gaps are fixed |

- 3. Define direct band gap and indirect band gap.**

Give example.

If the valence band and conduction band edges lie along same $k=0$ axis, the band gap is called direct band gap. e.g., Gallium arsenide

If the valence band and conduction band edges do not lie along the same $k=0$ axis, it is called indirect band gap e.g., silicon

4. Distinguish between direct band gap and indirect band gap semiconductors:

| Direct band gap semiconductors | Indirect band gap semiconductors |
|---|---|
| 1. The valence band and conduction band edges do not | 1. The valence band and band edges lie at same $k=0$ axis at same $k=0$ axis. |
| 2. Direct electron-hole recombination through a trap. | 2. electron and hole recombine can take place. (indirect recombination) |
| 3. Carrier life time is smaller | 3. Carrier life time is larger. |

5. Write an expression for the concentration of holes in the valence band of an intrinsic semiconductor.

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

where

- $m_h^* \rightarrow$ effective mass of hole
- $E_F \rightarrow$ Fermi energy level
- $E_v \rightarrow$ Energy corresponds to valence band
- $T \rightarrow$ Absolute temperature

6. What are extrinsic semiconductors? Give examples:

A semiconductor in which charge carriers originate from impurity atoms is called an impure semiconductor or extrinsic semiconductor.

e.g., N type silicon ; P-type silicon

In N-type silicon the charge carriers originate from pentavalent impurities. Similarly in P-type silicon the charge carriers originate from trivalent impurities.

7. What are N-type and P-type semiconductors?

Semiconductors doped with pentavalent impurities are called N-type semiconductors. e.g., silicon doped with phosphorous

Semiconductors doped with trivalent impurities are called P-type semiconductors. e.g., silicon doped with aluminium

8. What is Fermi level in a semiconductor?

Fermi level in a semiconductor is the energy level situated in the band gap of the semiconductor. It is exactly located at the middle of the band gap in the case of an intrinsic semiconductor

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

9. Write the expression for the electrical conductivity of an intrinsic semiconductor

Electrical conductivity

where $n_i \rightarrow$ Intrinsic carrier concentration

$\mu_e \rightarrow$ Mobility of electron and

$\mu_h \rightarrow$ Mobility of hole.

10. Write an expression for carrier concentration in n-type semiconductor.

$$n = \sqrt{2N_d} \left(\frac{2\pi m_e^* k_B T}{h^2} \right)^{\frac{3}{4}} \exp \frac{E_d - E_C}{2k_B T}$$

where $m_e^* \rightarrow$ effective mass of electron

$N_d \rightarrow$ Number of donor atoms per unit volume

$T \rightarrow$ Absolute temperature

11. Write an expression for carrier concentration in p-type semiconductor.

$$n = \sqrt{2N_a} \left(\frac{2\pi m_h^* k_B T}{h^2} \right)^{\frac{3}{4}} \exp \left(\frac{E_v - E_a}{2k_B T} \right)$$

where $m_h^* \rightarrow$ effective mass of hole

$N_a \rightarrow$ Number of acceptor atoms per unit volume

$T \rightarrow$ Absolute temperature

12. What are donor and acceptor impurities? Give example:

When a pentavalent impurity is added to a semiconductor, it can donate one electron to the semiconductor and the energy level of the fifth electron is called donor level. Since the pentavalent impurity atoms can donate negative charges they are called donor impurities or N-type impurities. e.g., P, As, Sb

When a trivalent impurity is added to a semiconductor, it accepts one electron from the semiconductor thereby creating an acceptor level. Since the trivalent impurity atoms accept negative charges they are called P-type impurities or acceptor impurities. e.g., Al, Ga and In

13. Define Hall effect and Hall voltage :

When a current carrying conductor is placed right angle to the applied magnetic field a transverse electric field will be produced. This effect is known as Hall effect.

Consider a specimen with rectangular cross-section is carrying current in the x-direction. If a constant magnetic field is applied along the z-direction, an emf will develop along the y-direction. This voltage developed is called Hall voltage.

14. What are the important applications of Hall effect?

- (i) The sign of the Hall co-efficient is used to identify whether the semiconductor is N-type or P-type
- (ii) The measure of Hall co-efficient gives the carrier concentration per unit volume.
- (iii) The mobility of carriers can be determined.
- (iv) The conductivity of a semiconductor can be determined by determining the carrier concentration and mobility.

15. Explain why Zn and Cd possess positive Hall co-efficient:

The Hall co-efficient is negative in most of the monovalent elements. But for elements like Zn and Cd, R_H is positive.

According to band theory of solids, a material with nearly filled valence band can give rise to negative electron mass or holes. Due to the possible hole conduction in Zn and Cd they have positive Hall co-efficient.

DESCRIPTIVE QUESTIONS

1. Derive the expressions for the electron and hole concentration in an intrinsic semiconductor. Show that the Fermi level lies midway between the valence band and conduction band.
2. Derive the expression for (i) The intrinsic conductivity (ii) Fermi level and (iii) Energy gap of an intrinsic semiconductor. Discuss how the energy gap of an intrinsic semiconductor is determined.
3. Derive the expression for electron concentration in a n-type semiconductor. Sketch the variation of Fermi level, electron concentration and conductivity of a n-type semiconductor.
4. Derive the expression for hole concentration in a p type semiconductor. Sketch the variation of Fermi level, hole concentration and conductivity of a p- type semiconductor.
5. Define Hall effect and Hall voltage. Derive the expression for the Hall co-efficient. Discuss how the Hall voltage is experimentally measured. What are the applications of Hall effect?