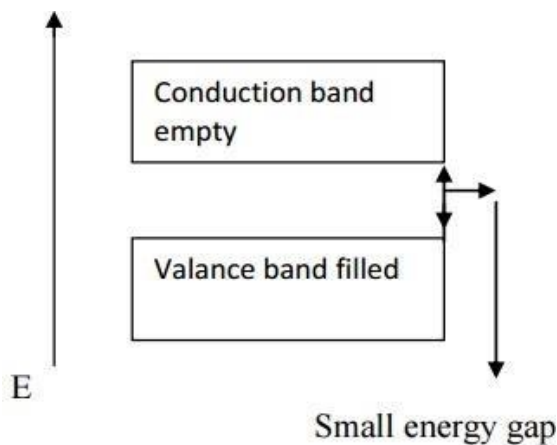# UNIT – II
SEMICONDUCTING MATERIALS

Based on electrical resistance

The resistivity of a semiconductor is lesser then an insulator but more than that of a conductor. It is in the order of 10^{-4} to 0.5 ohm metre.

Based on energy band

A semiconductor has nearly empty conduction band and almost filled valance band with very small energy gap ($\approx$ 1eV).

GENERAL PROPERTIES OF SEMICONDUCTORS

They are formed by covalent bonds.
They have an empty conduction band at 0K They have almost filled valance band They have small energy gap They posses crystalline structure
They have negative temperature co efficient of resistance
If the impurities are added to a semiconductor, its electrical conductivity increases. Similarly, if the temperature of the semiconductor increased, its electrical conductivity increases.

ELEMENTAL AND COMPOUND SEMICONDUCTORS

The semiconductors are classified mainly into two types based on composition of materials.
Elemental semiconductors Compound semiconductors Elemental semiconductors

These semiconductors are made from a single element of fourth group elements of the periodic table.
They are also known as indirect band gap semiconductors Example –Germanium, silicon

Compound semiconductors

Semiconductors which are formed by combining third and fifth group elements or second and sixth group elements in the periodic table are known as compound semiconductors. These compound semiconductors are also known as direct band gap semiconductors.

Example –1. Combination of third and fifth group elements Gallium phosphide (GaP)
Gallium arsenide (GaAs) Indium phosphide (InP) Indium arsenide (InAs)

2. Combination of second and sixth group elements Magnesium oxide (MgO) Magnesium

silicon (MgSi) Zinc oxide (ZnO) Zinc sulphide (ZnS)

Types of semiconductors
Based on the purity semiconductors are classified in to the following two types.
Intrinsic semiconductors Extrinsic semiconductors

Intrinsic semiconductors

A semiconductor in extremely pure form, without the addition of impurities is known as intrinsic semiconductors. Its electrical conductivity can be changed due to thermal excitation.

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

Extrinsic semiconductors

A semiconductor in extremely impure form, with the addition of impurities is known as extrinsic semiconductors.

2.   INTRINSIC SEMICONDUCTORS – ELECTRONS AND HOLES

We know that, at 0K intrinsic pure semiconductor behaves as insulator. But as temperature increases some electron move from valance band to conduction band as shown in fig. therefore both electrons in conduction band and holes in valance band will contribute to electrical conductivity. Therefore the carrier concentration (or) density of electrons (n_e) and holes (n_h) has to be calculated.
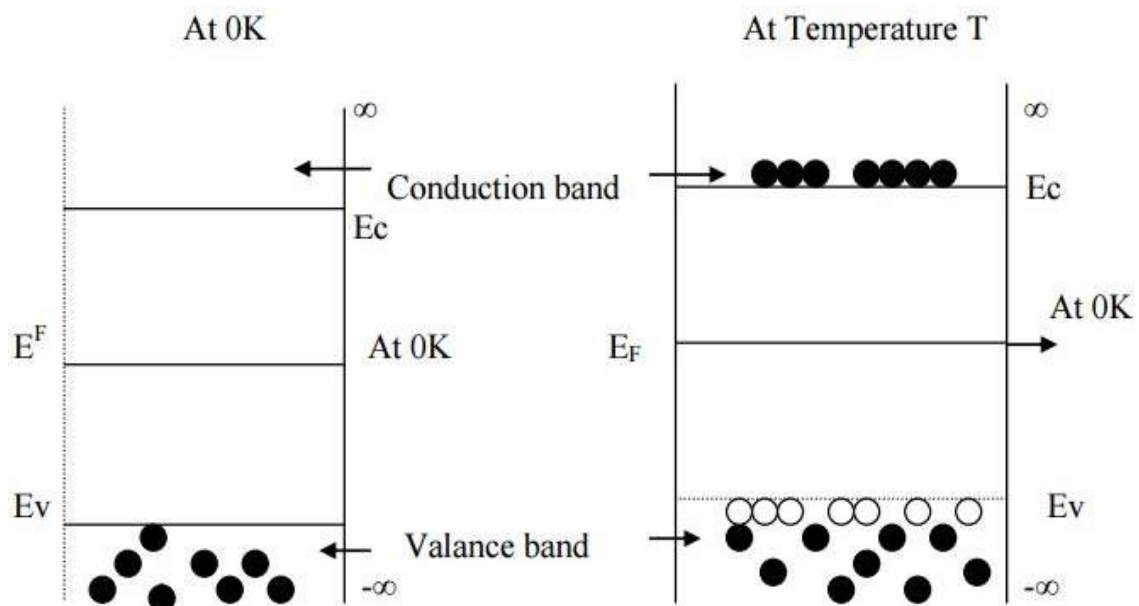
Assume that electron in the conduction band as a free electron of mass m^*_e and the hole in the valance band behave as a free particle of mass m^*_h. The electrons   in   the   conduction   band have   energies   Lying from Ec to ∞ and holes-∞intotheEv valanceasshownb Ec represents the lowest energy level of conduction band Ev represents the highest energy level of the valance band.

2. CARRIER CONCENTRATION IN AN INTRINSIC SEMICONDUCTOR

DENSITY OF ELECTRONS IN CONDUCTION BAND

Density of electrons on conduction band $n_e = \int_{Ec}^{\infty} Z(E).F(E)dE$ $\longrightarrow$ (1

From Fermi-Dirac statistics we can write

$$Z(E)dE = 2.\,\pi\,/\,4\,[8m^*e\,/\,h^2]^{3/2}\,E^{1/2}\,dE \longrightarrow (2)$$

Considering minimum energy of conduction band as Ec and maximum ene
we can write equation 2 as

$$Z(E)dE = \pi\,/\,2\,x\,[8m^*e\,/\,h^2]^{3/2}(E-Ec)^{1/2}\,dE \longrightarrow (3$$

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

Substituting equation 4 & 3 in equation 1 we have Density of electrons in conduction band within the limits Ec to ∞ as

Since to move an electron from valavce band to conduction band the energy required is greater then $4K_BT$ (i.e) $E - E_F >> K_BT$ (or) $(E - E_F)\,/\,K_BT >> 1$

$$\text{(or) } e^{(E-E_F)/K_BT} >> 1$$

$$1 + e^{(E-E_F)/K_BT} = e^{(E-E_F)/K_BT}$$

Equation 5 becomes

$$n_e = \pi\,/\,2\,x\,[8m^*e\,/\,h^2]^{3/2}\int_{Ec}^{\infty} \frac{(E-Ec)^{1/2}}{e^{(E-E_F)/K_BT}}\,.\,dE$$

$$n_e = \pi\,/\,2\,x\,[8m^*e\,/\,h^2]^{3/2}\int_{Ec}^{\infty} (E-Ec)^{1/2}\,e^{-(E-E_F)/K_BT}\,dE$$

$$n_e = \pi\,/\,2\,x\,[8m^*e\,/\,h^2]^{3/2}\int_{Ec}^{\infty} (E-Ec)^{1/2}\,e^{(E_F-E)/K_BT}\,dE \longrightarrow$$

Let us assume that $E - Ec = x\,K_BT$ Or $E = Ec + x\,K_BT$

Differentiating we get $dE = K_BT.\,dx$, Limits: when $E = Ec$; $x = 0$

When   E = ∞; x = ∞ Limits are 0 to ∞

Equation 6 can be written as

$$n_e = \pi/2 \times [8m^*e/h^2]^{3/2} \int_0^\infty (xK_BT)^{1/2} e^{(E_F - xK_BT - E_c)/K_BT} . K_BT \, dx$$

$$n_e = \pi/2 \times [8m^*e/h^2]^{3/2} \int_0^\infty (x)^{1/2} (K_BT)^{3/2} e^{(E_F - E_c)/K_BT} . e^{-x} dx$$

$$n_e = \pi/2 \times [8m^*e K_BT/h^2]^{3/2} e^{(E_F - E_c)/K_BT} \int_0^\infty (x)^{1/2} . e^{-x} dx$$

$$n_e = \pi/2 \times [8m^*e K_BT/h^2]^{3/2} e^{(E_F - E_c)/K_BT} \sqrt{\pi}/2 \qquad \left\{ \int_0^\infty (x)^{1/2} . e^{-x} dx \right.$$

$$n_e = 1/4 \times [8\pi m^*e K_BT/h^2]^{3/2} e^{(E_F - E_c)/K_BT}$$

Density of electrons in conduction band is

$$n_e = 2 . [2\pi m^*e K_BT/h^2]^{3/2} . e^{(E_F - E_c)/K_BT} \qquad \longrightarrow \quad (7$$

a. DENSITY OF HOLES IN VALANCE BAND

We know F(E) represents the probability of filled states. As the maximum probability 1, the probability of un filled states will be [1 –F(E)].

Example, if F(E) = 0.8 then 1 –F(E) = 0.2

(i.e) 80% chance of finding an electron in valance band and 20% chance of finding a hole in valance band.

Let the maximum energy in valance band be Ev and the minimum energy be -∞. Theref density of hole in valance band nh is given by

we know
$$n_h = \int_{-\infty}^{E_v} Z(E).[1 - F(E)]dE \qquad \longrightarrow \quad (8$$

$$Z(E)dE = \pi/2 \times [8m^*h/h^2]^{3/2}(E_v - E)^{1/2} dE \qquad \longrightarrow \quad (9$$

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

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

Here
$$E - E_F \ll K_BT, \quad (E-E_F)/K_BT \ll 1$$

$$e^{(E-E_F)/K_BT} \ll 1$$

$$1 + e^{(E-E_F)/K_BT} = 1$$

$$1 - F(E) = e^{(E-E_F)/K_BT} \qquad \longrightarrow \quad (10)$$

Substituting equation 10 & 9 in 8, we get

$$n_h = \pi/2 \times [8m^*h/h^2]^{3/2} \int_{-\infty}^{E_v} (E_v - E)^{1/2} e^{(E-E_F)/K_BT} dE \qquad \longrightarrow$$

Let us assume that
$$E_v - E = x K_BT,$$

Differentiating we get $dE = - K_BT. dx,$

Limits: when E = ∞;

Let us assume that Ev –E = x KBT,
Differentiating we get dE = - KBT. dx, Limits: when E = ∞;
When Ev –(-∞)   = x;   x   =   ∞ when E = Ev; x = 0

Limits   are   ∞   to   0 Equation 11 becomes

$$n_h = \pi/2 \times [8m^*_h/h^2]^{3/2} \int_\infty^0 (xK_BT)^{\frac{1}{2}} e^{(E_v \cdot xK_BT \cdot E_F)/K_BT} .(- K_BT) \, dx$$

to exclude the negative sign, the limits can be interchanged.

$$n_h = \pi/2 \times [8m^*_h/h^2]^{3/2} \int_0^\infty (x)^{\frac{1}{2}} (K_BT)^{3/2} e^{(E_v \cdot E_F)/K_BT} . e^{-x} dx$$

$$n_h = \pi/2 \times [8m^*_h K_BT/h^2]^{3/2} e^{(E_v \cdot E_F)/k_BT} \int_0^\infty (x)^{\frac{1}{2}} . e^{-x} dx$$

$$n_h = \pi/2 \times [8m^*_h K_BT/h^2]^{3/2} e^{(E_v \cdot E_F)/K_BT} \sqrt{\pi}/2 \qquad \left(\int_0^\infty (x)^{\frac{1}{2}} . e^{-x} dx = \cdots \right.$$

$$n_h = 1/4 \times [8 \pi m^*_h K_BT/h^2]^{3/2} e^{(E_v \cdot E_F)/K_BT}$$

Density of holes in valance band is

$$n_h = 2 . [2 \pi m^*_h K_BT/h^2]^{3/2} . e^{(E_v \cdot E_F)/K_BT} \qquad \longrightarrow (12)$$

b. DENSITY OF INTRINSIC CARRIER CONCENTRATION

In an intrinsic semiconductor, the concentration of electrons in the conduction band is equal to the concentration of holes in the valance band.

We can write $n_i = n_e = n_h$ & $n_i^2 = n_e . n_h$

Substituting equation 15 & 16, we have

$$n_i^2 = 2 . [2 \pi m^*_e K_BT/h^2]^{3/2} . e^{(E_F \cdot Ec)/k_BT} \times 2 . [2 \pi m^*_h K_BT/h^2]^{3/2} . e^{(E_v \cdot E_F)/\cdots}$$

$$n_i^2 = 4 [2 \pi K_BT/h^2]^3 . e^{(E_F - Ec + Ev - E_F)/k_BT} [m^*_e m^*_h]^{3/2}$$

$$n_i^2 = 4 [2 \pi K_BT/h^2]^3 . e^{(Ev \cdot Ec)/k_BT} [m^*_e m^*_h]^{3/2}$$

$$n_i^2 = 4 [2 \pi K_BT/h^2]^3 . e^{-Eg/k_BT} [m^*_e m^*_h]^{3/2}$$

Where Ec −Ev = Eg is the forbidden energy gap.

$$n_i = 2 \left[2\pi K_B T / h^2 \right]^{3/2} \cdot e^{-E_g/2k_BT} \left[m^*e \, m^*_h \right]^{3/4}$$

FERMI ENERGY LEVEL

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

(i.e) $n_e = n_h$

Equating equations 7& 12

$$\left[m^*e \right]^{3/2} \cdot e^{(E_F - E_c)/k_B T} =. \left[m^*_h \right]^{3/2} \cdot e^{(E_v - E_F)/k_B T}$$

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

$$= e^{(E_F - E_c - E_v + E_F)/k_B T}$$

$$= e^{(2E_F - (E_v + E_c))/k_B T}$$

Taking log on both on sides we have

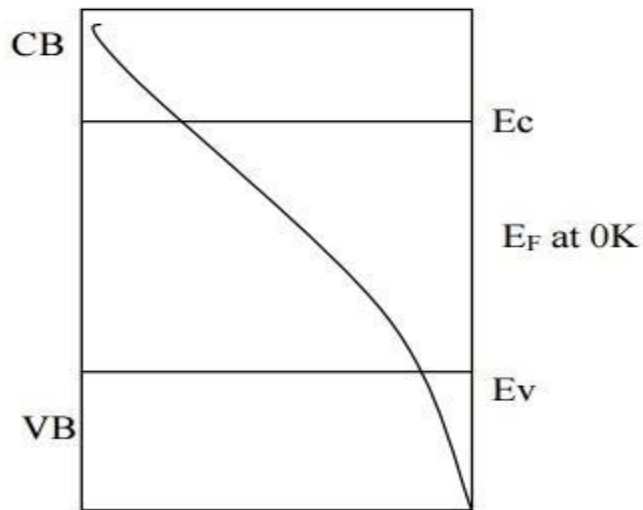$$3/2 \log \left(\frac{m^*h}{m^*_e} \right) = \frac{\left[2E_F - (E_v + E_c) \right]}{k_B T}$$

$$2E_F = E_v + E_c + \tfrac{3}{4} K_B T \log \left(\frac{m^*h}{m^*_e} \right)$$

$$E_F = \frac{E_v + E_c}{2} + \tfrac{3}{4} K_B T \log \left(\frac{m^*h}{m^*_e} \right) \longrightarrow$$

If m*h = m*e, then log m*h / m*e = 0 since log 1 = 0

(i.e) the Fermi energy level lies in the midway between Ec and Ev as shown fig (since at 0K, T = 0).

$$E_F = \left(\frac{E_v + E_c}{2} \right) \longrightarrow (14)$$

But in actual case $m*_h$ $m*_e$ and the Fermi energy level slightly increases with increase in temperature as shown in fig.

Mobility

When an electric field is applied to a semiconductor, the charge carrier namely electrons and holes attain drift velocity V_d. The drift velocity attained by the charge carrier is proportional to electric field strength E.

Drift velocity V_d is proportional to E

(i.e) $$V_d \; \alpha \; E$$

$$V_d = \mu \qquad E$$

Where μ is proportionality constant and it is known as the mobility of the charge carrier being considered. Mobility μ is defined as the velocity of a charge carrier produced unit field strength.

$$\mu = \frac{V_d}{E}$$

If $E = 1$ $\qquad \mu = V_d$

The electron and hole nobilities are denoted by the symbols μ_e and μ_h .

ELECTRICAL CONDUCTIVITY

Electrical conductivity of a semiconductor is different from that of a conductor. The charge carriers in a conductor are electrons. In the case of a semiconductor, both electron and holes are charge carriers. On the basis of free electron theory of solids, the electrical conductivity of metal is given by

$$\sigma = \mu \; ne \qquad \text{----(1)}$$

Using the equation 1, the electrical conductivity of a semiconductor due to electrons in the conduction band is given by

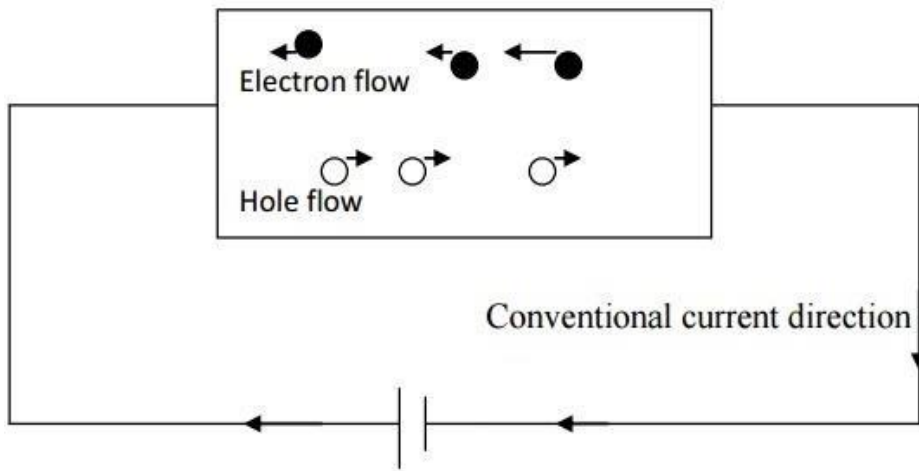$$\sigma_e = n_e \; e \, \mu_e \qquad \text{-----(2)}$$

Where n_e is the number of electrons per unit volume; e is the charge of an electron

μ_e is the electron mobility.

Similarly, the electrical conductivity of a semiconductor due to holes in the valance band is given by
$$\sigma_h = n_h \, e \, \mu_h \qquad \qquad \text{----(3)}$$

where n_h - is the hole density in the valance band; e - is the charge of a hole μ_h –is the hole mobility

Therefore the total electrical conductivit conductivities due to electrons and holes.

$$\sigma_i = \sigma_e + \sigma_h \qquad \qquad \text{---------(4)}$$
Substituting equations 2& 3 in the equation 4, We have

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

$$\sigma_i = e[\, n_e \, \mu_e + n_h \, \mu_h] \qquad \longrightarrow \quad (5)$$

For an intrinsic semiconductor, the number of electrons in the conduction band is equal to the number of holes in the valance band,
(i.e) $n_e = n_h = n_i$
Where n_i is the intrinsic carrier concentration.

Hence, the electrical conductivity of an intrinsic semiconductor is given by

$$\sigma_i = e[\, n_i \, \mu_e + n_i \, \mu_h]$$
Thus, the electrical conductivity depends upon the negative exponential of the
forbidden energy gap Eg and on the motilities' of both electron and holes.

d.   BAND GAP DETERMINATION

Electrical conductivity of an intrinsic semiconductor is given by

$$\sigma_i = 2e \, [2 \pi K_B T / h^2]^{3/2} \cdot e^{-Eg/2k_B T} \, [m^*e \, m^*_h]^{\frac{3}{4}} \, [\mu_e + \mu_h]$$

$$\sigma_i = A \, e^{-Eg/2k_B T} \qquad \longrightarrow \qquad (1)$$

Where constant $A = 2e \, [2 \pi K_B T / h^2]^{3/2} [m^*e \, m^*_h]^{\frac{3}{4}} [\mu_e + \mu_h]$

Resistivity of an intrinsic semiconductor,

$$\rho_i = 1/\sigma_i = 1/A \, e^{-Eg/2k_B T} = e^{Eg/2k_B T} / A \qquad \longrightarrow \qquad (2)$$

$$R_i \, a/l = e^{Eg/2k_B T} / A \qquad \longrightarrow \qquad (3)$$

[Since $\rho_i = R_i \, a/l$, Where R_i – Resistance of the semiconductor,

a- area of cross – section of semiconductor

l- Length of the semiconductor]

(or) $\qquad R_i = l \, e^{Eg/2k_B T} / A \, a \qquad \longrightarrow \qquad (4)$

$$R_i = C \, e^{Eg/2k_B T} \qquad [\text{since } C = l / Aa] \qquad \longrightarrow \qquad (5)$$

Taking log on both sides we have

$$\log R_i = \log (C \, e^{Eg/2k_B T})$$

$$\log R_i = \log C + \log e^{Eg/2k_B T}$$

$$\log R_i = \log C + Eg/2 K_B T \qquad \longrightarrow \qquad (6)$$

This equation (6) is similar to the equation of a straight line, $y = mx + c$ In equation (6), $y = \log R$; $x = 1/T$; $m = Eg/2 K_B T$ and $c = \log C$

From the equation 6, it is noted that by measuring the resistance of an i ntrinsic semiconductor at different temperatures, its forbidden energy gap Eg can be determined.

If a graph is drawn between log R and 1 / T, the value of Eg is determined from the slope of a straight line.
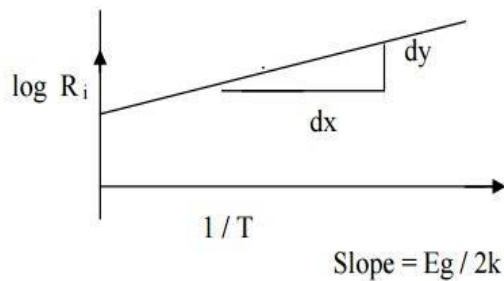
Slope = Eg / 2k

$$\text{Slope} = E_g / 2k$$

Eg = 2k X slope   ----(7) From the graph slope = dy / dx

Substituting the expression for the slope in equation (7), we have

Eg = 2k dy / dx Where, k is the Boltzmann'sconstant.

4. EXTRINSIC SEMICONDUCTOR

In a semiconducting material, if the charge carriers originate from impurity atoms added to the original material, then this type of semiconductor is called extrinsic or impure semiconductor. It is also known as doped semiconductor.

Doping

The method of adding impurities to a pure semiconductor is known as doping and impurity added is called doping agent or dopant.

The addition of impurities will increase the number of free electrons and holes in a semiconductor and hence increases its electrical conductivity.

Advantages of extrinsic semiconductor
1. Conductivity is high.

2. Conductivity can be controlled to any desired value through the control of doping concentration.

3. Conductivity is not a function of temperature.

Types of extrinsic semiconductor
The extrinsic semiconductors are classified into two types based on the type of impurity added.

(i). n –type semiconductor (ii). P –type semiconductor

N –TYPE SEMICONDUCTOR

When a small amount of pentavalent impurity (group V element) is added to a pure semiconductor, it becomes a n –semiconductor.. such impurities are known as donor impurities because they donate the free electrons to the semiconductor crystal.

A pentavalent impurity (arsenic) having five valance electrons is ad ded to a pure

semiconducting material having four valance electrons (silicon or germanium).

The four valance electrons of the impurity atoms bond with four valance electrons of the

semiconductor atom and remaining 1 electron of the impurity atom is left free as shown fig.

Therefore number of free electrons increases, as the electrons are produced in excess, they the majority charge carrier in n –type semiconductor and holes are the majority charge carriers.

Since electrons are donated in this type of semiconductor the energy level of these donated electrons is called donor energy level (E_d) as shown in fig.

E_d is very close to conduction band and hence even at room temperature the electrons are easily excited to conduction band. The current flow in this type of semiconductor is due to electrons.
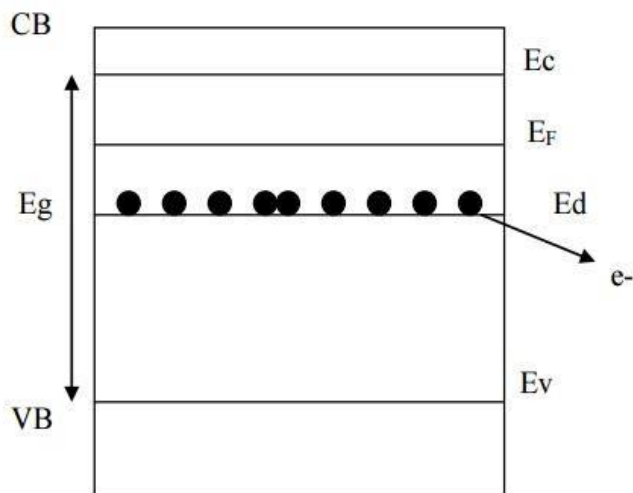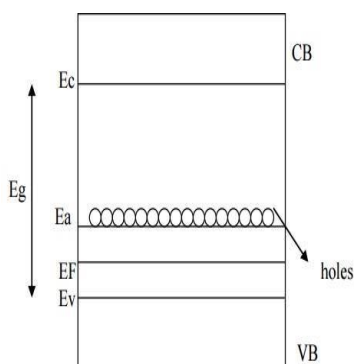

P –TYPE SEMICONDUCTOR

P –type semiconductor is obtained by doping an intrinsic semiconductor with trivalannt (3 electrons in valance band)impurity atoms like boron, gallium, indium etc.,

The three valance electrons of the impurity atom pairs with three valence electrons of the semiconductor atom and one position of the impurity atom remains vacant, this is called hole as shown in fig

Therefore the number of holes increased with impurity atoms added to it. Since holes are produced in excess, they are the majority charge carriers in p – type semiconductor and electrons are the minority charge carriers.

Since the impurity can accept the electrons this energy level is called acceptor energy level (E_a) and is present just above the valence band as shown in fig.


Here the current conduction is mainly due to holes (holes are shifted from one covalent bond to anther).

5. CARRIER CONCENTRATION IN N –TYPE SEMICONDUCTOR

FERMI ENERGY LEVEL

The energy band structure of n –type semiconductor is shown in fig. At 0 K, EF will lie exactly between Ec and Ed, but even at low temperature some electrons may go from Ed to Ec. Let us assume that Ec –EF > KBT. Then the density of electrons in conduction band can be written as

$$n_e = 2 \cdot [2\pi m^*e\, K_B T / h^2]^{3/2} \cdot e^{(E_F - Ec)/k_B T} \longrightarrow (1)$$
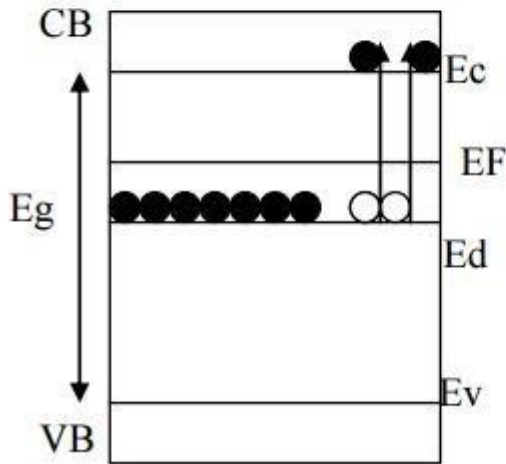
Let Nd be the number of donor energy levels per cm 3 (i.e) density of state Z(Ed) dE. If some electrons donated from donor energy level to conduction band say for example if two electrons goes to conduction band then two vacant sites (holes) will be created in Ed levels.

Thus in general we can write the density of holes in donor energy level as N(Ed) dE = Z(Ed) dE .(1 – F(Ed))

(i.e) n h = Nd .(1 –F(Ed))   ---(2)

$$1 - F(E_d) = 1 - \frac{1}{1+ e^{(E_d - E_F)/kT}}$$

$$1 - F(E) = \frac{e^{(E_d - E_F)/kT}}{1 + e^{(E_d - E_F)/kT}} \longrightarrow (3)$$

Here $E_d - E_F \ll K_B T$, $e^{(E_d - E_F)/K_B T} \ll 1$

$$e^{(E_d - E_F)/K_B T} \ll 1$$

$$1 + e^{(E_d - E_F)/K_B T} = 1$$

Equation 3 becomes

$$1 - F(E_d) = e^{(E_d - E_F)/k_B T} \longrightarrow (4)$$

$$1 - F(E_d) = e^{(E_d - E_F)/k_B T}$$

Substituting equation (4) in (2)

$$n_h = N_d \cdot e^{(E_d - E_F)/k_B T} \longrightarrow (5)$$

At equilibrium condition
Number of electrons per unit volume in conduction band (electron density) = Number of holes per unit volume in conduction band (hole density)
Equating equation (1) and equation (5) we get

$$2 \cdot [2 \pi m^*e\, K_B T / h^2]^{3/2} \cdot e^{(E_F - E_c)/k_B T} = N_d \cdot e^{(E_d - E_F)/k_B T} \longrightarrow ($$

$$\frac{e^{(E_F - E_c)/k_B T}}{e^{(E_d - E_F)/k_B T}} = \frac{N_d}{2 \cdot [2 \pi m^*e\, K_B T / h^2]^{3/2}}$$

$$e^{(E_F - E_c - E_d + E_F)/k_B T} = \frac{N_d}{2 \cdot [2 \pi m^*e\, K_B T / h^2]^{3/2}}$$

$$e^{(2E_F - (E_c + E_d))/k_B T} = \frac{N_d}{2 \cdot [2 \pi m^*e\, K_B T / h^2]^{3/2}}$$

Taking log on both sides

$$Log\, [e^{(2E_F - (E_c + E_d))/k_B T}] = log \left\{ \frac{N_d}{2 \cdot [2 \pi m^*e\, K_B T / h^2]^{3/2}} \right\}$$

$$\frac{2E_F - E_c + E_d}{K_B T} = log \left(\frac{N_d}{2 [2 \pi m^*e\, K_B T / h^2]^{3/2}} \right)$$

$$2E_F = E_c + E_d + K_B T\, log \left(\frac{N_d}{2 [2 \pi m^*e\, K_B T / h^2]^{3/2}} \right)$$

$$E_F = \frac{E_c + E_d}{2} + \frac{K_B T\, log}{2} \left(\frac{N_d}{2 [2 \pi m^*e\, K_B T / h^2]^{3/2}} \right)$$

When T = 0, we can write the above equation

$$E_F = \left(\frac{E_c + E_d}{2} \right) \longrightarrow$$

Equation (7) shows that, at 0K, EF will lie expertly in the midway between E_C and E_d.

DENSITY OF ELECTRON CONCENTRATION (n)

By substituting E_f value from equation (7) into expression

$$e^{(E_F - E_c)/k_B T}, \text{ we have,}$$

$$e^{(E_F - E_c)/k_B T} = \exp\left[\frac{E_c + E_d}{2 k_B T} - \frac{E_c}{k_B T} + \frac{1}{2} \log \frac{N_d}{2 [2 \pi m^*e\, K_B T / h^2]^{3/2}}\right]$$

$$e^{(E_F - E_c)/k_B T} = \exp\left[\frac{E_d - E_c}{2 k_B T} + \frac{1}{2} \log \frac{N_d}{2 [2 \pi m^*e\, K_B T / h^2]^{3/2}}\right]$$

$$= \exp\left(\frac{E_d - E_c}{2 k_B T}\right)\left[\frac{N_d}{2 [2 \pi m^*e\, K_B T / h^2]^{3/2}}\right]$$

By substituting equation (9) in (1), we have,

$$n = 2 [2 \pi m^*e\, K_B T / h^2]^{3/2} \exp\left(\frac{E_d - E_c}{2 k_B T}\right)\left[\frac{N_d}{2 [2 \pi m^*e\, K_B T / h}\right.$$

$$n = (2 N_d)^{1/2} [2 \pi m^*e\, K_B T / h^2]^{3/4} \exp\left[\frac{E_d - E_c}{2 k_B T}\right] \longrightarrow \quad (1$$

ELECTRICAL CONDUCTIVITY

We know that electrical conductivity in semiconductor is given by

$\sigma_n = n_e\, e\, \mu_e + n_h\, e\, \mu_h$

where $\mu_h = 0$ $\sigma_n = n_e\, e\, \mu_e$

$$\sigma_n = (2N_d)^{1/2}\,[2\pi m*e\, K_B T / h^2]^{3/4}\, \exp\left(\frac{E_d - E_c}{2k_B T}\right) e\, \mu_e \quad \underline{\hspace{2cm}}$$

This equation represent the electrical conductivity of n –type semiconductor.

VARIATION OF CARRIER CONCENTRATION WITH TEMPERATURE IN N – TYPE SEMICONDUCTOR

When the temperature increased some electrons in Ed level may be shifted to conduction band and hence some vacant sites will be created in Ed levels. Therefore the Fermi level shifts down to separate that empty levels and the filled valance band level as shown in fig.
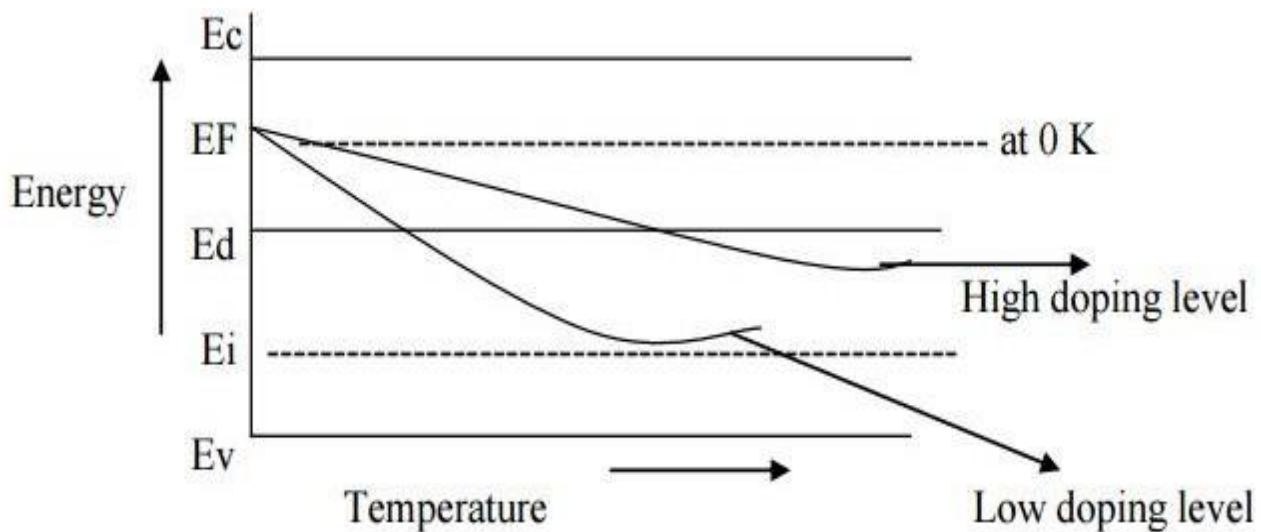
From the above figure it can be seen that for the same temperature, if the impurity atoms (i.e) doping level is increased, the electron concentration increases and hence Fermi level increases.

6. CARRIER CONCENTRATION AND FERMI LEVEL IN P –TYPE SEMICONDUCTOR

CARRIER CONCENTRATION

For p –type at absolute zero EF will be exactly between Ea and Ev. At low temperature some electron from valence band fills the holes in the acceptor energy level as shown in figure.

We know the density of holes in the valence band,

$$n_h = 2 \cdot [2\pi m^*_h K_B T / h^2]^{3/2} \cdot e^{(E_v - E_F)/k_B T} \longrightarrow (1)$$

$$2 \cdot [2\pi m^*_h K_B T / h^2]^{3/2} \cdot e^{(E_v - E_F)/k_B T} = \frac{Na}{e^{(Ea-E_F)/kT}}$$

$$e^{(E_v - E_F + Ea - E_F)/k_B T} = \frac{Na}{2 \cdot [2\pi m^*_h K_B T / h^2]^{3/2}}$$

$$e^{(E_v + Ea - 2E_F)/k_B T} = \frac{Na}{2 \cdot [2\pi m^*_h K_B T / h^2]^{3/2}}$$

Taking log on both sides

$$\log\left[e^{(E_v + Ea - 2E_F)/k_B T}\right] = \log\left(\frac{Na}{2 \cdot [2\pi m^*_h K_B T / h^2]^{3/2}} \right)$$

$$\frac{(E_v + E_a) - 2E_F}{K_B T} = \log\left(\frac{Na}{2 \cdot [2\pi m^*_h K_B T / h^2]^{3/2}} \right)$$

Let Na be the number of acceptor energy levels per cm 3 which has energy Ea above valence band. If some electrons are accepted by acceptor energy levels from the valence band, say for example if two electrons are accepted to fill the hole sites in the acceptor levels, then two holes will be created in the valence band as shown in fig .
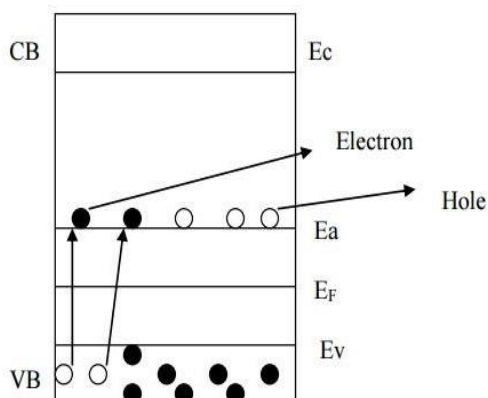
Therefore in general the electron density in the acceptor energy level can be written as

N(Ea) dE = Z(Ea) dE F(Ea)

$$N(E_a)\, dE = Z(E_a)\, dE \quad F(E_a)$$

$$(i.e)\ n_e = N_a\, .F(E_a) \longrightarrow \quad (2)$$

$$F(Ea) = \frac{1}{1+ e^{\,(Ea-E_F)/kT}}$$

$$Ea - E_F >> K_B T \ (or)\ (Ea - E_F) / K_B T >> 1$$

$$e^{\,(Ea - E_F)/K_B T} >> 1$$

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

$$F(Ea) = \frac{1}{e^{\,(Ea-E_F)/kT}} \longrightarrow \quad (3)$$

Substituting equation (3) in (2), we get

$$n\,e = \frac{N_a\ .}{e^{\,(Ea-E_F)/kT}} \longrightarrow \quad (4)$$

At equilibrium condition

Number of electrons per unit volume in conduction band (electron density) = Number of holes per unit volume in conduction band (hole density)

Equating equation (1) and equation (4) we get

FERMI ENERGY LEVEL

At 0K, when T= 0 we can write equation (5)

$$E_F = \frac{E_v + E_a}{2} - \frac{K_B T \log}{2} \left(\frac{N_a}{2\,[2\,\pi\, m^*h\, K_B T / h^2]^{3/2}} \right)$$

At 0K, when T= 0 we can write equation (5)

$$E_F = \left(\frac{E_v + E_a}{2} \right) \longrightarrow \quad (6)$$

7. VARIATION OF FERMI LEVEL WITH TEMPERATURE AND IMPURITY CONCENTRATION IN P-TYPE SEMICONDUCTOR

When the temperature is increased, some of the electrons in the valence band will go to the acceptor energy level by breaking up the covalent bonds and hence Fermi energy level shifted upward direction for doping level of $Nd = 10^{21}$ atoms / m^3 as shown in figure.

From the figure it can be seen that for the same temperature, if the impurity atoms (i.e) doping level is increased say $Nd = 10^{24}$ atoms /m^3, the hole concentration increases and hence the Fermi level decreases.
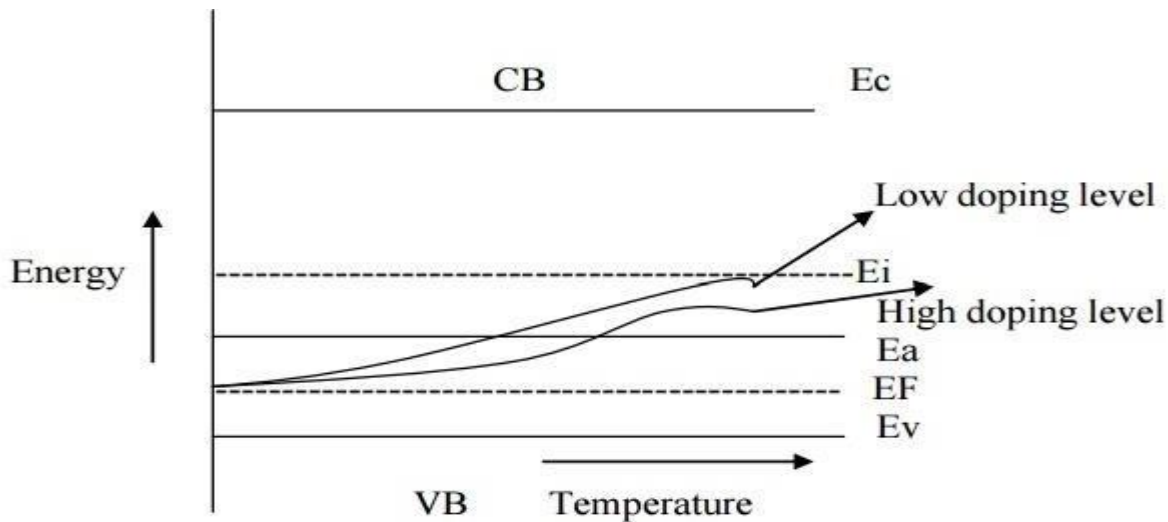
Therefore at low temperature the Fermi energy level may be increased up to the level of intrinsic energy level (Ei).

8. HALL EFFECT

Measurement of conductivity will not determine whether the conduction is due to electron or holes and therefore it will be very difficult to distinguish between p –type and n- type semiconductors.

Therefore Hall Effect is used to distinguish between the two types of charge carriers and their carrier densities and is used to determine the mobility of charge carriers.

STATEMENT

When a conductor (metal or semiconductor) carrying current (I) is placed perpendicular to a magnetic field (B), a potential difference (electric field) is developed inside the conductor in a direction perpendicular to both current and magnetic field. This phenomenon is known as Hall Effect and the voltage thus generated is called Hall voltage.

THEORY

Hall effect in n- type semiconductor

Let us consider a n-type semiconductor material in the form of rectangular slab. In such a material current flows in X –direction and magnetic field B applied in Z- direction. As a result, Hall voltage is developed along Y –direction as shown in figure.
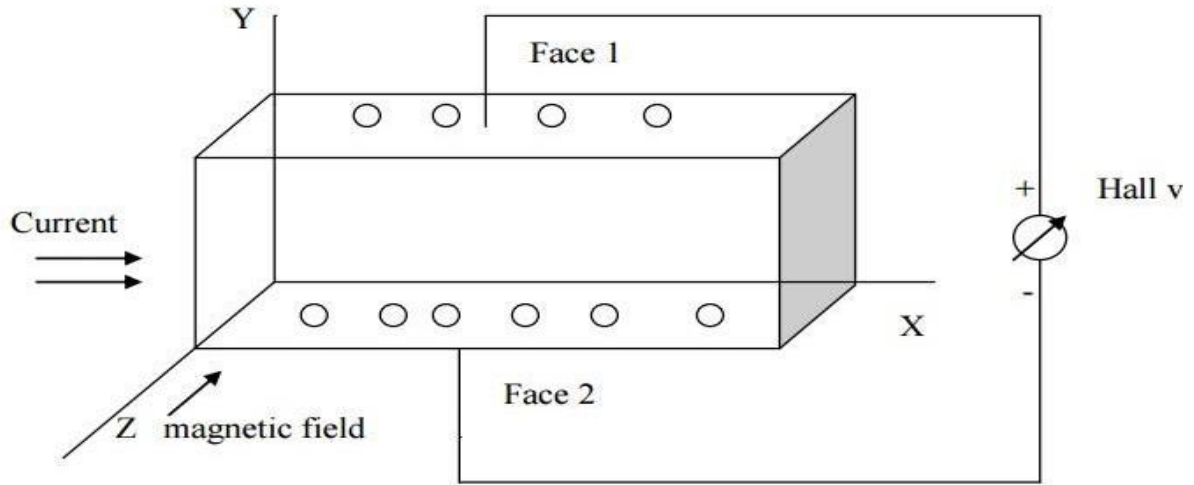
Since the direction of current is from left to right the electrons moves from right to left in X-direction as shown in fig

Now due to magnetic field applied the electron moves towards downward direction with velocity v and cause negative charge to accumulate at face (1) of the material as shown in fig. therefore the potential difference is established between the face (2) and face (1) of the specimen which gives rise to EH in the negative Y direction.
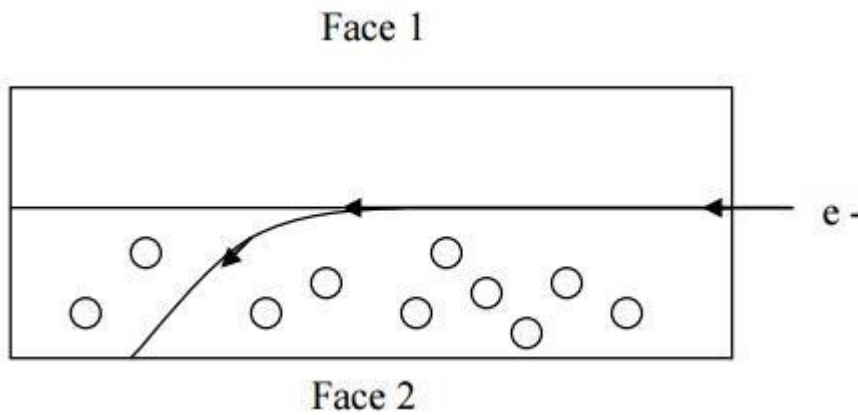
Here, the force due to potential difference = -e E_H ---(1)

Force due magnetic field = - Bev   ---(2)

At equilibrium equation (1) = equation (2)
-e E_H = - Bev
E_H = Bv   ---(3)
We know the current density Jx in the X- direction is Jx = -n_e ev
v = - Jx / n_e e   ---(4)
Substituting equation (4) in equation (3) we get
E_H = - B Jx / n_e e   ----(5)
E_H = R_H . Jx . B   ----(6)
Where R_H is known as the Hall co –efficient, is given by

$RH = -(1 / ne \ e)$ ----(7)

The negative sign indicates that the field is developed in the negative Y – direction.

Hall effect in p –type semiconductor

Let us consider a p –type semiconducting material for which the current is passed along X – direction from left to right and magnetic field is applied along Z – direction as shown in fig. since the direction of current is from left to right, the holes will also move in the same direction as shown in fig.
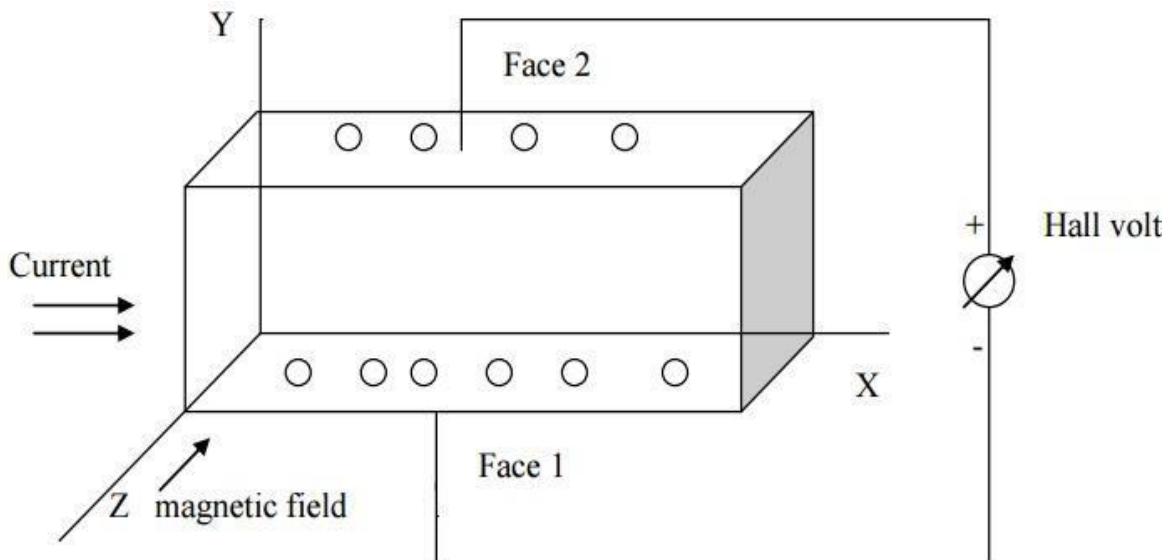
Now due to magnetic field applied the holes moves towards downward direction with velocity v and accumulates at the face (1). A potential difference is established between face (1) and (2) in the positive Y - direction.
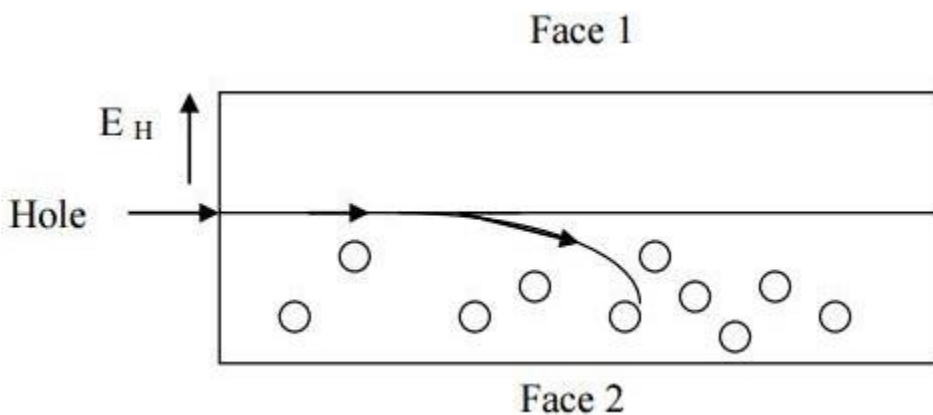
Here, the force due to potential difference $= -e \ E_H$ ----(8)

Force due magnetic field $= Bev$ ----(9)

At equilibrium equation (1) = equation (2) $e \ E_H = Bev$

$E_H = Bv$ --------------(10)

We know the current density J_x in the X- direction is $J_x = nh \ ev$

$v = Jx / n_h\ e$ ----------(11)

Substituting equation (4) in equation (3) we get

$$E_H = B\ Jx / n_h\ e$$

$$E_H = R_H \cdot Jx \cdot B$$

Where R_H is known as the Hall co –efficient, is given by $R_H = (1 / n_h\ e)$ ----(12)

The positive sign indicates that the field is developed in the positive Y –direction

Hall coefficient in terms of hall voltage

If the thickness of the sample is t and the voltage developed is VH, then Hall voltage $V_H = E_H \cdot t$ ---(13)

Substituting equation (6) in equation (13), we have $V_H = R_H\ Jx\ B \cdot t$ ----(14)

If b is the width of the sample then

Area of the sample = b.t

Current density = $Jx = Ix / bt$ -----(15)

Substituting equation (15) in equation (14) we get

$$V_H = \frac{R_H\ Ix\ Bt}{bt}$$

$$V_H = \frac{R_H\ Ix\ B}{b}$$

$$\text{Hall coefficient, } R_H = \frac{V_H\ b}{Ix\ B} \longrightarrow \quad (16)$$

The sign for VH will be opposite for n and p type semiconductors.

Mobility of charge carriers

We know that Hall coefficient,

$$R_H = -(1 / n_e\ e)$$

The above expression is valid only for conductors where the velocity is taken as the drift velocity.

But for semiconductor velocity is taken as average velocity so RH for n- type semiconductor is modified as

$$R_H = -3\pi / 8[1/n_e e]$$

$$R_H = -1.18 / n_e e \quad \longrightarrow (1)$$

We know the conductivity for n – type is $\sigma_e = n_e e \mu_e$

Or $\quad \mu_e = \sigma_e / n_e e \quad \longrightarrow (2)$

From equation (1) we can write

$$1 / n_e e = -R_H / 1.18 \quad \longrightarrow (3)$$

Substituting equation (3) in equation (2) we get

$$\mu_e = -[\sigma_e R_H / 1.18]$$

We know that, $R_H = \dfrac{V_H B}{I_x B}$

For n –type semiconductor, the mobility of electron is

$$\mu_e = -[\sigma_e / 1.18]\left(\dfrac{V_H B}{I_x B}\right) \quad \longrightarrow (4)$$

Similarly for p –type semiconductor, the mobility of hole is

$$\mu_h = [\sigma_h / 1.18]\left(\dfrac{V_H B}{I_x B}\right) \quad \longrightarrow (5)$$

EXPERIMENTAL DETERMINATION OF HALL EFFECT

A semiconducting material is taken in the form of a rectangular slab of thickness t and breadth b. A suitable current Ix ampere is passed through this sample along X- axis by connecting it to a battery.
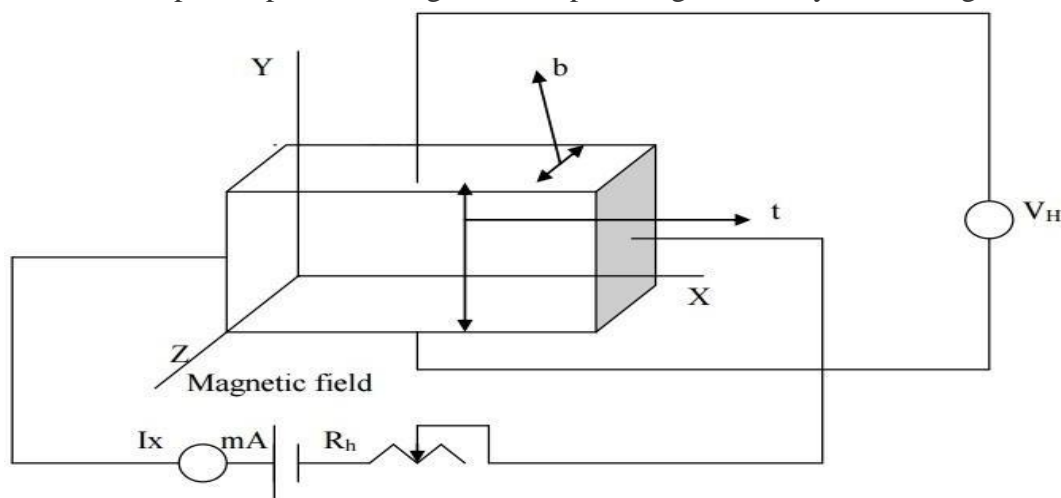
This sample is placed in between two poles of an electro magnet such that magnetic field is applied along Z –axis.

Due to Hall Effect, Hall voltage (V_H) is developed in the sample. This voltage measured by fixing two probes at the centers of the bottom and top faces faces of the sample. By measuring Hall voltage, Hall coefficient is determined from the formula

From the hall coefficient, carrier concentration and mobility can be determined.

$$\text{Hall coefficient, } R_H = \frac{V_H \, b}{I_x \, B}$$

APPLICATIONS OF HALL EFFECT

It is used to determine whether the material is p-type or n-type semiconductor.

(ie) if RH is negative then the material n-type. If the RH is positive then the material p-type.

1. It is used to find the carrier concentration
2. It is used to find the mobility of charge carriers μ_e, μ_h.
3. It is used to find the sign of the current carrying charges.
4. It is used to design magnetic flux meters and multipliers on the basis of Hall voltage.
5. It is used to find the power flow in an electromagnetic wave.