

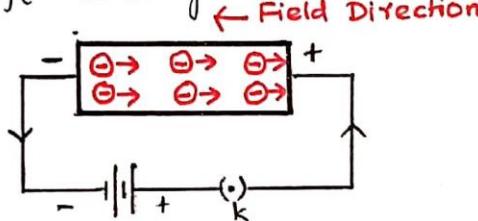
Expression for the Electrical Conductivity:Definition:-

It is the quantity of Electric charges flowing per unit time ( $t$ ) per unit area ( $A$ ) maintained at a unit potential gradient ( $E$ ).

$$\sigma = \frac{Q}{tAE} = \frac{ne^2C}{m} \text{ A}^{-1} \text{ m}^{-1}$$

Derivation:

When an electrical field applied to an electron of charge ' $e$ ', it moves in a opposite direction with the applied field with a constant velocity ( $v_d$ ) known as "drift velocity"



Here the force experienced by the electron by external field

$$F = eE \quad \text{--- (1)}$$

and the acceleration gained by the electron ' $a$ ' is given by

$$\text{acceleration } a = \frac{\text{velocity}}{\text{Time}} = \frac{v_d}{\tau}$$

$$\therefore a = \frac{v_d}{\tau}$$

$$v_d = a\tau \quad \text{--- (2)}$$

We know that from Newton's II law,

$$F = ma \quad \text{--- (3)}$$

By comparing eqns ① & ③

$$eE = ma$$

$$a = \frac{eE}{m} \quad \text{--- (4)}$$

Substituting eqn ④ in eqn ②

$$v_d = \frac{eE\tau}{m} \quad \text{--- (5)}$$

If  $n \rightarrow$  no. of free electron  
 $e \rightarrow$  charge of an electron

Then current density in terms of ' $v_d$ ' is given by

$$J = nev_d \quad \text{--- (6)}$$

Substitute eqn ⑤ in eqn ⑥

$$J = ne \frac{eE\tau}{m}$$

$$J = \frac{ne^2 E \tau}{m} \quad \text{--- (7)}$$

From the definition of charge density is directly proportional to applied electric field.

$$J \propto E$$

$$J = \sigma E \quad \text{--- (8)}$$

Comparing eqns ⑦ & ⑧ we get

$$\sigma E = \frac{ne^2 C}{m}$$

$$\boxed{J = \frac{ne^2 C}{m}} \quad \text{--- (9)}$$

Eqn ⑨ is the expression for the electrical conductivity.

## Thermal Conductivity:

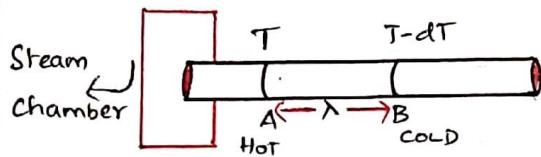
### Definition:-

It is the amount of heat conducted per unit area ( $A$ ), per unit time ( $t$ ) maintained at unit temperature gradient.

$$K = \frac{Q}{dT/dx} = \frac{n e^2 K_B \tau}{2}$$

### Derivation:-

Consider a uniform metallic rod contain free electron.



Here  $A \& B \rightarrow$  cross-sectional area near hot & cold end

$T, T-dT \rightarrow$  Temp at A & B.

$\lambda \rightarrow$  Mean free path

The average K.E of electrons crossing A

$$E_1 = \frac{1}{2} m v^2 = \frac{3}{2} K_B T \quad \text{--- (1)}$$

W.K.T K.E of free electron at 'B'

$$E_2 = \frac{3}{2} K_B (T-dT) \quad \text{--- (2)}$$

Excess energy carried out by electrons from A to B

$$K.E = \frac{3}{2} K_B T - \frac{3}{2} K_B (T-dT)$$

$$= \frac{3}{2} K_B T - \frac{3}{2} K_B T + \frac{3}{2} K_B dT$$

$$K.E = \frac{3}{2} K_B dT \quad \text{--- (3)}$$

Assume, the electron can move in all possible direction, then the no. of electron crossing per unit area, per unit time from 'A' to 'B'.

$$n = \frac{1}{6} n^0 \quad \text{--- (4)}$$

$\therefore$  The excess average energy carried from A to B is given by

$$E = \frac{1}{6} n^0 \times \frac{3}{2} K_B dT$$

$$E = \frac{1}{4} n^0 K_B dT \quad \text{--- (5)}$$

Hence the net amount of heat transformed from 'A' to 'B'.

$$Q = \frac{1}{4} n^0 K_B dT - \left[ -\frac{1}{4} n^0 K_B dT \right]$$

$$Q = \frac{1}{2} n^0 K_B dT \quad \text{--- (6)}$$

from the definition, we know that

$$Q = K \cdot \frac{dT}{dx}$$

$$Q = K \cdot \frac{dT}{\lambda} \quad \text{--- (7)}$$

By comparing eqn (7) & (6)

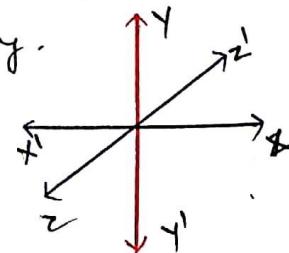
$$K \frac{dT}{\lambda} = \frac{1}{2} n^0 K_B dT$$

$$K = \frac{1}{2} n^0 K_B \lambda \quad \text{--- (8)}$$

w.k.t  $\lambda = \tau \sigma$

$$\therefore K = \frac{1}{2} n^0 K_B \tau \sigma \quad \text{--- (9)}$$

Eqn (9) is the expression for thermal conductivity.



Wiedemann-Franz LawDefinition:-

The ratio between thermal conductivity to the electrical conductivity is directly proportional to the absolute temperature

$$\frac{K}{\sigma} \propto T$$

$$\frac{K}{\sigma} = LT$$

where  $L \rightarrow$  Lorenz no.  
 $L = 1.12 \times 10^{-8} \text{ W} \cdot \text{K}^2$

Derivation:-

It is derived from the expression of electrical & thermal conductivity we know that

$$\sigma = \frac{ne^2c}{m}$$

$$K = \frac{1}{2} n e^2 k_B T$$

$$\therefore \frac{K}{\sigma} = \frac{\frac{1}{2} n e^2 k_B T}{\frac{ne^2c}{m}} = \frac{m e^2 k_B}{2e^2} = \frac{k_B}{e^2} \frac{m^2}{2}$$

We know that  $\frac{1}{2} m v^2 = \frac{3}{2} k_B T$

$$\therefore \frac{K}{\sigma} = \frac{3}{2} \frac{k_B^2 T}{e^2} = \frac{3}{2} \left( \frac{k_B}{e} \right)^2 T$$

$$\frac{K}{\sigma} = LT$$

where  $L = \frac{3}{2} \left[ \frac{k_B}{e} \right]^2$

This law holds good for low temp.

Postulates of free electron theory:-

① A metal consists of large no. of free electrons. These electrons move freely throughout the volume of the metal.

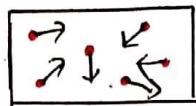
② They move randomly in all possible directions just like the gas molecules move in a container.

③ In the absence of an electric field

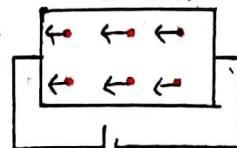
the free electrons move in all directions in a random manner.

They collide with other free electrons and positive ion core during the motion.

As the motion is random, the resultant velocity in any particular direction is zero.



Electrons in absence  
of Elec. field



e's in applied  
elec. field.

④ When the electric field is applied ~~with~~ the electrons get some amount of energy. These electrons move towards the potential.

As a result of collision, the free electrons acquire a constant avg. velocity known as drift velocity.

⑤ The velocity & the energy distribution of free electrons are governed by classical Maxwell distribution function.

Success of classical free elec. theory:-

\* It is used to

\* Verify Ohm's law

\* Explain electrical & thermal conductivities of metal.

\* Derive Wiedemann-Franz law.

\* Explain optical properties of metals

Failures of Classical free elec. theory:-

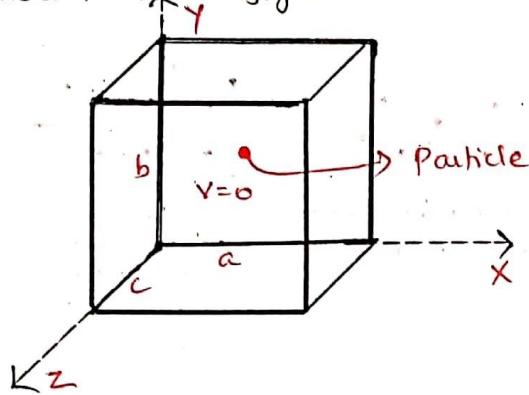
\* Elec & thermal conductivities of semi cond. & insulators cannot be explained by this theory.

\* All the free electrons absorb the supplied energy. But practically only few e's absorb energy

\* Photo-elec. effect, Compton effect cannot be explained by this theory.

### Particle in 3D Box:

Consider a particle of mass 'm' moving three dimensionally in a box of lengths  $a, b$  &  $c$  as shown in the figure.



The potential function is given by

$$V(x, y, z) = 0 \text{ for } 0 < x < a \\ 0 < y < b \\ 0 < z < c$$

$$V(x, y, z) = \infty \text{ for } 0 \geq x \geq a \\ 0 \geq y \geq b \\ 0 \geq z \geq c$$

The solution of one dimensional potential box can be extended for a three dimensional box.

In 3 dimensional box, instead of one quantum number 'n', we have to use three quantum numbers  $n_x, n_y$  and  $n_z$  corresponding to the three coordinate axes namely x, y and z respectively.

The Eigen function and eigen value of a particle moving in a one dimensional potential well can be derived as follows.

One dimensional Schrödinger's time independent wave equation of a free particle is given by

$$\frac{d^2\psi}{dx^2} + \frac{2ME}{\hbar^2} \psi = 0 \quad \text{--- (1)}$$

$$\text{Substituting } \frac{2ME}{\hbar^2} = k^2 \text{ in eqn (1)}$$

$$\frac{d^2\psi}{dx^2} + k^2 \psi = 0 \quad \text{--- (2)}$$

The general solution of eqn (2) is given by

$$\psi(x) = A \sin kx + B \cos kx \quad \text{--- (3)}$$

Where A and B are two constants A & B can be determined by boundary conditions.

### Condition - 1

$$\psi = 0 \text{ at } x = 0.$$

$$\text{--- (3)} \Rightarrow 0 = A \sin 0 + B \cos 0$$

$$0 = 0 + B \times 1$$

$$B = 0$$

### Condition - 2

$$\psi = 0 \text{ at } x = a$$

$$\text{--- (3)} \Rightarrow 0 = A \sin ka + 0$$

$$A \sin ka = 0$$

It is found that either  $A=0$  or  $\sin ka=0$

Since  $B=0$ , 'A' cannot be zero

$$\therefore \sin ka = 0$$

$$\text{(ie)} \quad ka = n\pi$$

$$k = \frac{n\pi}{a}$$

$$k^2 = \frac{n^2\pi^2}{a^2} \quad \text{--- (4)}$$

We know that

$$k^2 = \frac{2mE}{\hbar^2} = 2mE \cdot \frac{4\pi^2}{h^2}$$

$$k^2 = \frac{8\pi^2 m E}{h^2} \quad \text{--- (5)}$$

Comparing eqns (4) & (5)

$$\frac{n^2\pi^2}{a^2} = \frac{8\pi^2 m E}{h^2}$$

$$E_n = \frac{n^2 h^2}{8ma^2} \quad \text{--- (6)}$$

Substituting  $k = \frac{n\pi}{a}$  in eqn (3)

$$\Psi_n(x) = A \sin \frac{n\pi x}{a} \quad \text{--- (7)}$$

The constant 'A' can be determined by normalisation of wave function

The value of 'A' is given

$$\text{by } A = \sqrt{\frac{2}{a}}$$

$$\therefore \text{Eqn (7)} \Rightarrow \Psi_n(x) = \sqrt{\frac{2}{a}} \sin \frac{n\pi x}{a} \quad \text{--- (8)}$$

The eqn(6) and eqn(8) give eigen value and eigen function of a particle moving in an one dimensional box.

These two equations can be extended to three dimensional potential box as follows.

Energy of the particle

$$E_{nxnynz} = E_{nx} + E_{ny} + E_{nz}$$

$$E_{nxnynz} = \frac{n_x^2 h^2}{8ma^2} + \frac{n_y^2 h^2}{8mb^2} + \frac{n_z^2 h^2}{8mc^2}$$

$$E_{nxnynz} = \frac{h^2}{8m} \left[ \frac{n_x^2}{a^2} + \frac{n_y^2}{b^2} + \frac{n_z^2}{c^2} \right] \quad \text{--- (9)}$$

The corresponding normalised wave function of the particle in the three dimensional box is given by

$$\Psi_{nxnynz} = \sqrt{\frac{2}{a}} \sin \left( \frac{n_x \pi x}{a} \right) \sqrt{\frac{2}{b}} \sin \left( \frac{n_y \pi y}{b} \right) \sqrt{\frac{2}{c}} \sin \left( \frac{n_z \pi z}{c} \right)$$

$$\Psi_{nxnynz} = \sqrt{\frac{2}{a}} \sqrt{\frac{2}{b}} \sqrt{\frac{2}{c}} \sin \left( \frac{n_x \pi x}{a} \right) \sin \left( \frac{n_y \pi y}{b} \right) \sin \left( \frac{n_z \pi z}{c} \right)$$

$$\Psi_{nxnynz} = \sqrt{\frac{8}{abc}} \sin \left[ \frac{n_x \pi x}{a} \right] \sin \left[ \frac{n_y \pi y}{b} \right] \sin \left[ \frac{n_z \pi z}{c} \right] \quad \text{--- (10)}$$

The eqns (9) & (10) give the eigen value and eigen function of a particle in 3D Box.

For cubical box  $a = b = c$

$\therefore$  The eigen value and eigen function are given by

$$E_{nxnynz} = \frac{h^2}{8ma^2} [n_x^2 + n_y^2 + n_z^2]$$

$$\Psi_{nxnynz} = \sqrt{\frac{8}{a^3}} \sin \left[ \frac{n_x \pi x}{a} \right] \sin \left[ \frac{n_y \pi y}{a} \right] \sin \left[ \frac{n_z \pi z}{a} \right]$$

### Fermi Distribution function:-

#### Definition:

It is the probability of occupation of electrons among different energy levels at absolute temperature.

It is given by

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

where  $E \rightarrow$  Energy level to be considered.

$E_F \rightarrow$  Fermi energy level.

$k_B \rightarrow$  Boltzmann Constant

$T \rightarrow$  Absolute Temperature.

If  $F(E)=1$ , the energy level is occupied by an electron.

If  $F(E)=0$ , the energy level is vacant.

If  $F(E)=0.5$ , then there is 50% chance for the electron to occupy.

#### Case (i)

If  $E < E_F$  at  $T=0K$

$$\begin{aligned} \text{Then } F(E) &= \frac{1}{1 + e^{(E-E_F)/k_B T}} \\ &= \frac{1}{1 + e^{(E-E_F)/0}} \\ &= \frac{1}{1 + e^{-\infty}} = \frac{1}{1 + 0} = 1 \end{aligned}$$

$$F(E) = 1$$

Thus at  $T=0K$ , 100% chance for the electrons to occupy the energy levels.

#### Case (ii)

If  $T=0K$  at  $E > E_F$

$$\begin{aligned} \text{Then } F(E) &= \frac{1}{1 + e^{(E-E_F)/k_B T}} \\ &= \frac{1}{1 + e^{\infty}} = \frac{1}{1 + \infty} \end{aligned}$$

$$F(E) = 0$$

Thus 0% chance for the electron to occupy the energy levels.

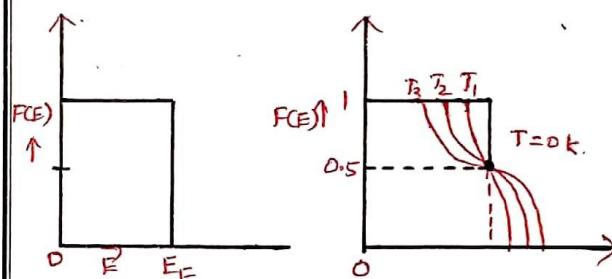
#### Case (iii)

If  $T > 0K$  at  $E = E_F$

$$F(E) = \frac{1}{1 + e^0} = \frac{1}{1 + 1}$$

$$F(E) = \frac{1}{2} \quad \text{or} \quad F(F) = 0.5$$

There is 50% chance for the electrons to occupy the fermi energy level



Variation of  $E_F$  with respect to temperature.

When  $T=0K$ , occupation is upto  $E_F$ .

When  $T > 0K$  valence electrons got breakdown in its bond and exited to conduction band.

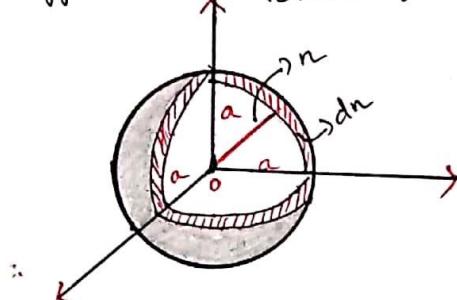
## Density of Energy States:-

### Definition:

It is defined as the no. of available energy states presented per unit volume of a metal piece.

$$z(E)dE = \frac{N(E)dE}{V}$$

$$\text{Density of Energy States} = \frac{\text{No. of available energy state between } E \text{ & } E+dE}{\text{Volume of a metal}}$$



Let us consider a sphere inside a cubical metal piece of side 'a'.

- \* Here  $n_x, n_y, n_z$  are the coordinate axes.

- \*  $n$  → inner radius of the sphere.

- \* ~~E~~ and  $E+dE$  are the energy of the inner and outer shell of the sphere.

- \* The sphere consists of no. of shells, between inner and outer shell each represents a energy level.

The no. of available energy states within the thickness of the sphere of radius 'n'

$$n = \frac{1}{8} \left[ \frac{4\pi n^3}{3} \right] \quad \text{--- (1)}$$

Hence the energy states within the sphere of radius  $(n+dn)$

$$n+dn = \frac{1}{8} \left[ \frac{4}{3} \pi (n+dn)^3 \right] \quad \text{--- (2)}$$

Hence, the no. of available energy states between  $(n & n+dn)$  the energy interval  $E$  and  $E+dE$ .

$$\begin{aligned} N(E)dE &= \frac{1}{8} \left[ \frac{4}{3} \pi (n+dn)^3 - \frac{4}{3} \pi n^3 \right] \\ &= \frac{1}{8} \left[ \frac{4}{3} \pi (n^3 + 3n^2dn + 3n^2dn^2 + dn^3) \right] \end{aligned}$$

$$N(E)dE = \frac{1}{8} \left[ \frac{4}{3} \pi (3n^2dn + 3ndn^2 + dn^3) \right]$$

$\because dn$  very small, neglecting the higher orders,

$$N(E)dE = \frac{1}{8} \left[ \frac{4}{3} \pi (3n^2dn) \right]$$

$$N(E)dE = \frac{\pi}{2} n^2 dn \quad \text{--- (3)}$$

We know that

the energy of an electron in a cubical metal piece. of side 'a' is

$$E = \frac{n^2 h^2}{8ma^2} \quad \text{--- (4)}$$

Differentiating eqn (4) we have

$$dE = \frac{2n dn \cdot h^2}{8ma^2}$$

$$(4) \quad ndn = \frac{8ma^2}{2h^2} \cdot dE \quad \text{--- (5)}$$

From eqn (4)

$$n^2 = \frac{8ma^2}{h^2} E$$

$$n = \left[ \frac{8ma^2 E}{h^2} \right]^{1/2} \quad \text{--- (6)}$$

Hence eqn ③ can be written as

$$N(E)dE = \frac{\pi}{2} n \cdot n dn \quad \text{--- (7)}$$

By substituting eqn ⑤ & ⑥ in ⑦

$$N(E)dE = \frac{\pi}{2} \left[ \frac{(8m)^{1/2} \alpha E^{1/2}}{h} \right] \left[ \frac{8m^2 dE}{2h^2} \right]$$

$$\therefore N(E)dE = \frac{\pi}{2} \frac{(8m)^{3/2} \alpha^3 E^{1/2} dE}{2h^3} \quad \text{--- (8)}$$

Here  $\alpha^3 = V \rightarrow \text{volume}$

$\therefore$  Density of energy states

$$Z(E)dE = \frac{N(E)dE}{V}$$

$$Z(E)dE = \frac{\pi (8m)^{3/2} \alpha^3 E^{1/2} dE}{4h^3 \cdot V}$$

$$Z(E)dE = \frac{\pi (8m)^{3/2} E^{1/2} dE}{4h^3} \quad \text{--- (9)}$$

According to Pauli's exclusion

Principle in each state 2 electrons can be accommodated.

$$\therefore Z(E)dE = 2 \times N(E)dE$$

$$\therefore Z(E)dE = 2 \times \frac{\pi}{4h^3} (8m)^{3/2} E^{1/2} dE$$

$$Z(E)dE = \frac{\pi}{2h^3} (8m)^{3/2} E^{1/2} dE \quad \text{--- (10)}$$

### Carrier Concentration in Metals:

The no. of electrons per unit volume in a given energy interval is calculated by

$$n_c = \int Z(E) F(E) dE \quad \text{--- (11)}$$

We know that

$$Z(E)dE = \frac{\pi}{2h^3} (8m)^{3/2} E^{1/2} dE$$

$$\begin{aligned} &= \frac{\pi}{2h^3} (8)^{3/2} (m)^{3/2} E^{1/2} dE \\ &= \frac{\pi}{2h^3} (4)^{3/2} \cdot (2)^{3/2} (m)^{3/2} E^{1/2} dE \\ &= \frac{\pi}{2h^3} 2^3 (2m)^{3/2} E^{1/2} dE \end{aligned}$$

$$Z(E)dE = \frac{4\pi}{h^3} (2m)^{3/2} E^{1/2} dE \quad \text{--- (12)}$$

~~If~~  $F(E)=1$  for energy levels

$$E=0 \text{ to } E=E_{f_0}$$

Then eqn (11) becomes

$$n_c = \frac{4\pi}{h^3} (2m)^{3/2} \int_0^{E_{f_0}} E^{1/2} dE$$

$$n_c = \frac{4\pi}{h^3} (2m)^{3/2} \left[ \frac{E^{3/2}}{3/2} \right]_0^{E_{f_0}}$$

$$= \frac{4\pi}{h^3} (2m)^{3/2} \cdot \frac{2}{3} [E_{f_0}]^{3/2}$$

$$n_c = \frac{8\pi}{3h^3} (2m E_{f_0})^{3/2} \quad \text{--- (13)}$$

### Fermi Energy:-

From eqn (13), we know that the carrier concentration  $n_c$  can be written as

$$n_c = \frac{8\pi}{3h^3} (2m)^{3/2} (E_{f_0})^{3/2}$$

$$\frac{3n_c}{8\pi} \frac{h^3}{(2m)^{3/2}} = [E_{f_0}]^{3/2}$$

By raising power on both sides

$$\text{by } 2/3$$

$$E_{f_0} = \left[ \frac{3n_c}{8\pi} \frac{h^3}{(2m)^{3/2}} \right]^{2/3}$$

$$E_{f_0} = \left[ \frac{3n_c}{8\pi} \right]^{2/3} \left[ \frac{h^2}{2m} \right] \quad \text{--- (14)}$$

Effective Mass of Electron:-Definition:-

The mass acquired by an electron, when it is accelerated in a periodic potential is called effective mass ( $m^*$ )

Derivation:-

Consider a crystal subjected to electric field ( $E$ ). Then the velocity gained by the electrons is described by the wave vector ( $k$ ) & it is equivalent to the wave packet moving with a group velocity ( $v_g$ ).

$$v_g = \frac{d\omega}{dk} \quad \text{--- (1)}$$

where  $\omega \rightarrow$  angular velocity ( $2\pi\nu$ )  
 $k \rightarrow$  wave vector.

We know that

$$E = h\nu \quad (\text{or}) \quad \omega = 2\pi\nu$$

$$\nu = \frac{\omega}{2\pi}$$

$$E = \frac{h\omega}{2\pi}$$

$$E = \hbar\omega$$

$$\hbar = \frac{h}{2\pi}$$

$$\omega = \frac{E}{\hbar} \quad \text{--- (2)}$$

$\therefore$  Eqn (1) can be written as

$$v_g = \frac{d}{dk} \left[ \frac{E}{\hbar} \right]$$

$$v_g = \frac{1}{\hbar} \left[ \frac{dE}{dk} \right] \quad \text{--- (3)}$$

Under this condition the acceleration  $a'$  of an electron

$$a' = \frac{dv_g}{dt}$$

$$= \frac{d}{dt} \left[ \frac{1}{\hbar} \left( \frac{dE}{dk} \right) \right]$$

$$a = \frac{1}{\hbar} \frac{d^2E}{dk^2} \cdot \frac{dk}{dt} \quad \text{--- (4)}$$

The momentum of an electron from de-Broglie wavelength

$$P = \frac{h}{\lambda}$$

$$P = \frac{h}{2\pi} \cdot \frac{2\pi}{\lambda}$$

$$P = \hbar \frac{2\pi}{\lambda}$$

$$P = \hbar k \quad \text{--- (5)}$$

Differentiate eqn (5) w.r.t. 't'

$$\frac{dp}{dt} = \hbar \frac{dk}{dt} \quad (\text{or}) \quad \frac{dk}{dt} = \frac{F}{\hbar} \quad \text{--- (6)}$$

[Force acting on the electron  $F = \frac{dp}{dt}$ ]

Hence eqn (4) can be written as

$$a = \frac{1}{\hbar} \cdot \frac{d^2E}{dk^2} \cdot \frac{F}{\hbar}$$

$$a = \frac{F}{\hbar^2} \frac{d^2E}{dk^2}$$

$$F = \left[ \frac{\hbar^2}{\left( \frac{d^2E}{dk^2} \right)} \right] a \quad \text{--- (7)}$$

When an electric field is applied, acceleration of the electron due to field.

$$a = \frac{eE}{m^*} = \frac{F}{m^*}$$

$$F = m^* a \quad \text{--- (8)}$$

Comparing eqns (7) & (8)

$$m^* a = \left[ \frac{\hbar^2}{\left( \frac{d^2E}{dk^2} \right)} \right] a$$

$$m^* = \frac{\hbar^2}{\left(\frac{d^2E}{dk^2}\right)} \quad \text{--- (9)}$$

Eqn ⑨ → Effective mass of an electron is not constant, but depends on the value  $\frac{d^2E}{dk^2}$

Case(i):  $\frac{d^2E}{dk^2} = +ve$ ,  $m^* = +ve$

Case(ii)  $\frac{d^2E}{dk^2} = -ve$ ,  $m^* = -ve$

Case(iii)  $\frac{d^2E}{dk^2} \rightarrow$  more,  $m^*$  is higher  
Lesser

Case(iii)  $\frac{d^2E}{dk^2} \rightarrow$  less  $m^*$  is large.

### Tight Binding Approximation:-

Before discussing about the tight binding approximation, let us know about free electron approximation.

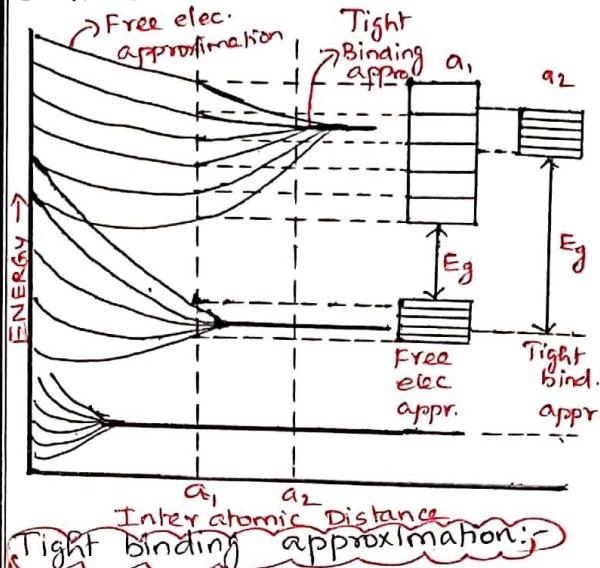
### Free electron approximation:-

In solids, ionic core which are tightly bounded to lattice location exists. The electrons are free to move throughout the solid. This is called the free electron approximation.

In free electron approximation,

- \* The P.E of the  $e^-$  is assumed to be lesser than its total energy.
- \* The width of the band gap ( $E_g$ ) are smaller than the allowed band. (fig)
- \* The interaction between the neighbouring atoms will be very strong.

\* As the atoms are closer to each other, the inter atomic distance decreases and hence the wave functions overlap with each other.



Tight binding approximation:-

Instead of beginning with the solid core, we begin with the electrons, (ie) all the electrons are bounded to the atoms. In other words, atoms are free while the electrons are tightly bounded. This is called tight bound approximation.

In tight binding approximation:

- \* The P.E of the electrons is nearly equal to the total energy
- \* The width of the forbidden bands ( $E_g$ ) are larger than the allowed bands.
- \* Therefore the interactions between the neighbouring atom will be weak.
- \* As the atoms are not closer, the interatomic distance increases and hence the wave functions will not overlap.

Carrier Concentration - Intrinsic Semiconductor:-

- Elemental
- Indirectgap

The no. of charge carriers per unit volume of the material is called carrier concentration also known as density of charge carriers.

Derivation:

In intrinsic semiconductor the no. of electrons in the conduction band ( $n$ ) and holes in the valence band ( $p$ ) is equal to each other at  $T > 0K$ .

$$n = p = n_i$$

The density of electrons in the conduction band ( $n$ ) is given by

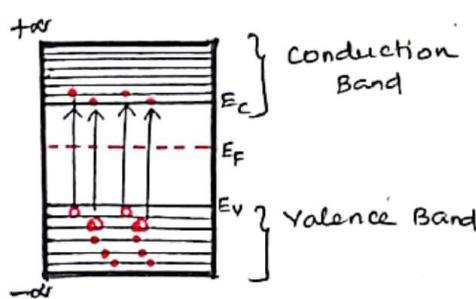
$$\int_{E_C}^{\infty} dz (CE) F(E) dE \quad \text{--- (1)}$$

We know that, Density of energy states

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

Probability of Electron occupation

$$F(E) = \frac{1}{1 + e^{\frac{(E-E_F)}{k_B T}}} \quad \text{--- (3)}$$



$$\therefore n = \int_{E_C}^{\infty} \frac{4\pi}{h^3} (2m_e^*)^{3/2} E^{1/2} \frac{1}{1 + e^{\frac{(E-E_F)}{k_B T}}} dE \quad \text{--- (4)}$$

Here

$m_e^*$  - Effective mass of electron.

$E$  - KE of conduction electron

$$E = E - E_C$$

$E_C$  - Lower conduction Energy level.

Eqn (4) can be written

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} \int_{E_C}^{\infty} \frac{(E-E_C)^{1/2}}{1 + e^{\frac{(E-E_F)}{k_B T}}} dE \quad \text{--- (5)}$$

We know that at  $T > 0K$

$$E - E_F \gg k_B T$$

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

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

Hence eqn (5) can be written as

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} \int_{E_C}^{\infty} \frac{(E-E_C)^{1/2}}{e^{\frac{(E-E_F)}{k_B T}}} dE$$

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} \int_{E_C}^{\infty} (E-E_C)^{1/2} e^{\frac{E_F-E}{k_B T}} dE$$

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} R^{\frac{E_F-E_C}{k_B T}} \int_{E_C}^{\infty} (E-E_C)^{1/2} e^{-\frac{E-E_C}{k_B T}} dE \quad \text{--- (6)}$$

To calculate eqn (6)

$$\begin{aligned} \text{Let } \\ E - E_C = x \\ E = x + E_C \\ dE = dx \end{aligned}$$

when	$E = E_C$	$E = \infty$
$E_C - E_C = x$	$x = 0$	$\infty - E_C = x$
		$x = \infty$

∴ Eqn ⑥ can be written as

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} e^{\frac{E_f - E_c}{k_B T}} \int_0^\infty x^{1/2} e^{-\frac{(E_f - E_c)x}{k_B T}} dx$$

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} e^{\frac{(E_f - E_c)}{k_B T}} \int_0^\infty x^{1/2} e^{-\frac{x}{k_B T}} dx$$

Using gamma function

$$\int_0^\infty x^{1/2} e^{-x/k_B T} dx = \frac{\sqrt{\pi}}{2} (k_B T)^{3/2}$$

Hence

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} e^{\frac{(E_f - E_c)}{k_B T}} \frac{\sqrt{\pi}}{2} (k_B T)^{3/2}$$

$$n = 2 \left[ \frac{2\pi m_e^* k_B T}{h^3} \right]^{3/2} e^{\frac{(E_f - E_c)}{k_B T}} \quad \text{--- (8)}$$

Eqn ⑧ is the expression for the density of electrons in a conduction band.

**Density of Holes (P) :-**

It is given by

$$\int_{E_1}^{E_2} dP = P = \int_{E_1}^{E_2} Z(E) dE [1 - F(E)] \quad \text{--- (9)}$$

Here

$$Z(E) dE = \frac{4\pi}{h^3} (2m_h^*)^{3/2} e^{V_2} dE$$

here

$$m = m_h^*$$

$$E = E_V - E$$

$$1 - F(E) = 1 - \frac{1}{1 + e^{\frac{(E - E_f)}{k_B T}}}$$

By Substituting and Simplifying

No. density of holes

$$P = 2 \left[ \frac{2\pi m_h^* k_B T}{h^3} \right] e^{\frac{(E_V - E_f)}{k_B T}} \quad \text{--- (10)}$$

**Expression for intrinsic carrier concentration.**

As we know in intrinsic Semiconductor at any temperature above  $T > 0K$

$$n = p = n_i \quad \text{--- (11)}$$

$$n \times p = n_i \times n_i = n_i^2$$

Hence

$$n_i^2 = n \times p \text{ given by}$$

$$n_i^2 = 2 \left[ \frac{2\pi m_e^* k_B T}{h^3} \right]^{3/2} e^{\frac{(E_f - E_c)}{k_B T}} \times 2 \left[ \frac{2\pi m_h^* k_B T}{h^3} \right]^{3/2} e^{\frac{(E_V - E_f)}{k_B T}}$$

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

$$n_i = 2 \left[ \frac{2\pi k_B T}{h^3} \right]^{3/2} (m_e^* m_h^*)^{3/4} e^{-\frac{E_g}{2k_B T}} \quad \text{--- (13)}$$

Eqn ⑬ is the expression for the carrier concentration of intrinsic Semiconductor.

**Density of Holes! :-**

It is given by

$$\int_{E_1}^{E_2} dP = P = \int_{E_1}^{E_2} Z(E) dE \cdot [1 - F(E)]$$

Hence

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

$$\text{Here } m = m_h^*$$

$$E = E_v - E$$

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

Eqn ①

$$P = \int_{-\infty}^{E_v} \frac{4\pi}{h^3} (2m_h^*)^{3/2} (E_v - E)^{1/2} e^{-(E-E_F)/k_B T} dE$$

$$P = \frac{4\pi}{h^3} (2m_h^*)^{3/2} e^{-E_F/k_B T} \int_{-\infty}^{E_v} (E_v - E)^{1/2} e^{E/k_B T} dE$$

- (2)

Let

$E_v - E = x$	When $E = -\infty$	When $E = E_v$
$E = E_v - x$	$E_v - (-\infty) = x$	$E_v - E_v = x$
$dE = -dx$	$E_v + \infty = x$	$x = 0$
	$x = \infty$	

Eqn ② becomes

$$P = \frac{4\pi}{h^3} (2m_h^*)^{3/2} e^{-(E_F/k_B T)} \int_0^\infty x^{1/2} e^{(E_v-x)/k_B T} dx$$

$$P = \frac{4\pi}{h^3} (2m_h^*)^{3/2} e^{-(E_F/k_B T)} \int_0^\infty x^{1/2} e^{-x/k_B T} dx$$

Using Gamma function

$$\int_0^\infty x^{1/2} e^{-x/k_B T} dx = \frac{\sqrt{\pi}}{2} [k_B T]^{3/2}$$

Hence

$$P = \frac{4\pi}{h^3} [2m_h^*]^{3/2} e^{\frac{E_v-E_F}{k_B T}} \frac{\sqrt{\pi}}{2} (k_B T)^{3/2}$$

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

The above equation is the expression for the density of holes in the valence band.

### Extrinsic Semiconductor

Def:

Impure Semiconductors are the one in which charge carriers generated by adding impure atoms to the pure semiconductors.

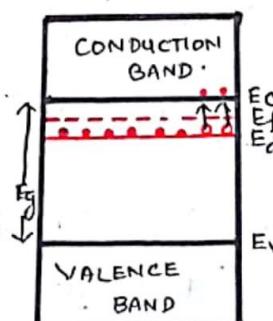
### Types:

These are classified into two types based on the type of impurity

- (i) n type (penta valent impurity)
- (ii) p type (Trivalent, impurity)

### Carrier Concentration - n type Semiconductor

\* The energy level diagram is shown in the figure.



\* The energy level of excess electron is called donor energy level (Ed). This is located above valence band.

$k_B T$  the density of electrons in the conduction band

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

$m_e^*$  → Effective mass  
 $k_B$  → Boltzmann constant

$$\text{No. of holes (or) donors} = N_d [1 - F(E_d)] \quad \text{--- (2)}$$

$F(E_d)$  → Probability of Electron in donor energy level.

$1 - F(E_d)$  → Probability of ionized donors

$N_d$  → Total no. of donor atoms per unit volume.

$$\therefore F(E_d) = \frac{1}{1 + e^{\frac{(E_d - E_f)}{k_B T}}}$$

∴ Eqn. (2)

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

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

$$= N_d \frac{e^{\frac{(E_d - E_f)}{k_B T}}}{1 + e^{\frac{(E_d - E_f)}{k_B T}}}$$

$E_d < E_f$  therefore  $E_d - E_f$  → ve

$$\therefore 1 + e^{\frac{(E_d - E_f)}{k_B T}} \approx 1$$

∴ The above eqn can be written as

$$\text{The density of ionised donors (or) holes } n_h = N_d e^{\frac{(E_d - E_f)}{k_B T}}$$

At equilibrium

$$\left. \begin{aligned} \text{Density of Electron in the conduction Band (n)} \\ \end{aligned} \right\} = \left. \begin{aligned} \text{Density of holes in the Donor energy level (n_h)} \\ \end{aligned} \right\}$$

$$\therefore n = n_h$$

$$2 \left[ \frac{2\pi m_e^* k_B T}{h^2} \right]^{3/2} e^{\frac{(E_f - E_C)}{k_B T}} = N_d e^{\frac{(E_d - E_f)}{k_B T}} \quad \text{--- (3)}$$

By Rearranging the above eqn

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

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

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

Taking log on both sides

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

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

$$2E_f = E_C + E_d + k_B T \log \left[ \frac{N_d}{2 \left[ \frac{2\pi m_e^* k_B T}{h^2} \right]^{3/2}} \right]$$

$$E_f = \frac{E_C + E_d}{2} + \frac{k_B T}{2} \log \left[ \frac{N_d}{2 \left[ \frac{2\pi m_e^* k_B T}{h^2} \right]^{3/2}} \right] \quad \text{--- (4)}$$

### Carrier Concentration:-

By substituting eqn ④ in eqn ① we have

$$n = 2 \left[ \frac{2\pi m_e^* k_B T}{h^2} \right]^{3/2} \exp \left[ \frac{E_d + E_C}{2} + \frac{k_B T}{2} \log \frac{N_d}{2 \left[ \frac{2\pi m_e^* k_B T}{h^2} \right]^{3/2}} \right]$$

$$n = 2 \left[ \frac{2\pi m_e^* k_B T}{h^2} \right]^{3/2} \exp \left[ \frac{E_d + E_C}{2k_B T} + \frac{E_C}{k_B T} + \frac{1}{2} \log \frac{N_d}{2 \left[ \frac{2\pi m_e^* k_B T}{h^2} \right]^{3/2}} \right]$$

$$n = 2 \left[ \frac{2\pi m_e^* k_B T}{h^2} \right]^{3/2} \exp \left[ \frac{E_d + E_C - 2E_C}{2k_B T} + \frac{1}{2} \log \frac{N_d}{2 \left[ \frac{2\pi m_e^* k_B T}{h^2} \right]^{3/2}} \right] \quad \text{--- (5)}$$

$$n = 2 \left[ \frac{2\pi m_e^* k_B T}{h^2} \right]^{3/2} e^{\frac{E_d - E_C}{2k_B T}} \cdot e^{\log \left[ \frac{N_d}{2 \left[ \frac{2\pi m_e^* k_B T}{h^2} \right]^{3/2}} \right]^{1/2}}$$

$$n = 2 \left[ \frac{2\pi m_e^* k_B T}{h^2} \right]^{3/2} e^{\frac{E_d - E_C}{2k_B T}} \cdot \frac{N_d^{1/2}}{2 \sqrt[4]{\frac{2\pi m_e^* k_B T}{h^2}}}$$

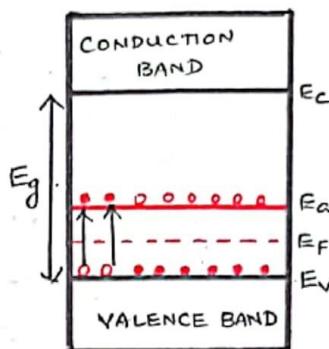
$$\boxed{n = \left[ 2 N_d \right]^{1/2} \left[ \frac{2\pi m_e^* k_B T}{h^2} \right]^{3/4} e^{\left[ \frac{E_d - E_C}{2k_B T} \right]}}$$

Eqn ⑥ is the expression for Carrier Concentration of n-type Semiconductor, in terms

### P-Type Semiconductor:

\* The Energy level diagram is shown in the figure

\* Here the excess no. of holes from a new energy level ( $E_A$ ) acceptor level just below the Conduction Band.



We know that the density of holes in the valence band.

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

$E_V$  → Top energy level of valence Band

$E_A$  → Acceptor Energy level

$E_F$  → Fermi Energy level.

Density of Electrons in the acceptor energy level is given by

$$n_e = N_a [F(E_A)]$$

$$n_e = N_a \frac{1}{1 + e^{(E_A - E_F)/k_B T}} \quad \text{--- (2)}$$

Since  $E_A - E_F \gg k_B T$  (or)  $\frac{E_A - E_F}{k_B T} \gg 1$

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

$$\therefore n_e = N_a e^{\frac{(E_F - E_A)}{k_B T}} \quad \text{--- (3)}$$

At equilibrium,

No. electrons in the acceptor energy level ( $n_e$ ) = No. of holes in Valence band ( $n_e$ )

$$2 \left[ \frac{2\pi m_h^* k_B T}{h^2} \right]^{3/2} e^{\frac{(E_V - E_F)}{k_B T}} = N_a e^{\frac{(E_F - E_A)}{k_B T}} \quad \text{--- (4)}$$

$$\frac{e^{\left(\frac{E_V - E_F}{k_B T}\right)}}{e^{\left(\frac{E_F - E_A}{k_B T}\right)}} = \frac{N_A}{2 \left[ \frac{2\pi m_h^* k_B T}{h^2} \right]^{3/2}}$$

$$e^{\left[ \frac{E_V - E_F - E_F + E_A}{k_B T} \right]} = \frac{N_A}{2 \left[ \frac{2\pi m_h^* k_B T}{h^2} \right]^{3/2}}$$

$$e^{\left[ \frac{-2E_F + E_V + E_A}{k_B T} \right]} = \frac{N_A}{2 \left[ \frac{2\pi m_h^* k_B T}{h^2} \right]^{3/2}}$$

Taking log on both sides,

$$\frac{-2E_F + E_V + E_A}{k_B T} = \log \frac{N_A}{2 \left[ \frac{2\pi m_h^* k_B T}{h^2} \right]^{3/2}}$$

Rearranging Equation,

$$E_F = \frac{E_A + E_V}{2} - \frac{k_B T}{2} \log \frac{N_A}{2 \left[ \frac{2\pi m_h^* k_B T}{h^2} \right]^{3/2}}$$

— (b)

The density of holes in the p type can be written by substituting equation (b) in eqn ①

$$P = 2 \left[ \frac{2\pi m_h^* k_B T}{h^2} \right]^{3/2} e^{\left[ \frac{E_V - E_F}{k_B T} \right]}$$

Here  $e^{\left[ \frac{E_V - E_F}{k_B T} \right]}$  can be rearranged as

$$= \exp \left[ \frac{E_V - \left[ \frac{E_A + E_V}{2} \right]}{k_B T} - \frac{k_B T}{2} \log \frac{N_A}{2 \left[ \frac{2\pi m_h^* k_B T}{h^2} \right]^{3/2}} \right]$$

$$= \exp \left[ \frac{2E_V - E_A - E_V}{2k_B T} + \frac{1}{2} \log \frac{N_A}{2 \left[ \frac{2\pi m_h^* k_B T}{h^2} \right]^{3/2}} \right]$$

$$= \exp \left[ \frac{E_V - E_A}{2k_B T} + \frac{1}{2} \log \frac{N_A}{2 \left[ \frac{2\pi m_h^* k_B T}{h^2} \right]^{3/2}} \right]$$

∴ Eqn ① can be written as

$$P = 2 \left[ \frac{2\pi m_h^* k_B T}{h^2} \right]^{3/2} \exp \left[ \frac{E_V - E_A}{2k_B T} + \frac{1}{2} \log \frac{N_A}{2 \left[ \frac{2\pi m_h^* k_B T}{h^2} \right]^{3/2}} \right]$$

$$P = 2 \left[ \frac{2\pi m_h^* k_B T}{h^2} \right]^{3/2} e^{\frac{E_V - E_A}{2k_B T}} \cdot \frac{(N_A)^{1/2}}{\left[ 2 \left[ \frac{2\pi m_h^* k_B T}{h^2} \right]^{3/2} \right]^{1/2}}$$

$$P = (2N_A)^{1/2} \left[ \frac{2\pi m_h^* k_B T}{h^2} \right]^{3/4} e^{\frac{(E_V - E_A)/k_B T}{2}}$$

(7)

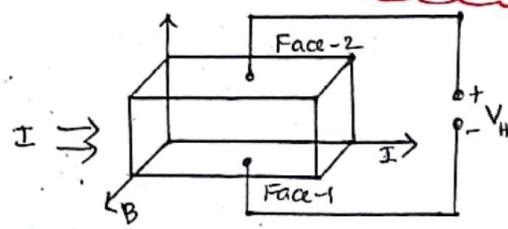
Eqn (7) is the expression for the carrier concentration of 'P'-type Semiconductor.

### Hall Effect:-

When a conductor carrying a current (I) is placed perpendicular to a magnetic field (B) a potential difference is produced inside the conductor in a direction perpendicular to current and magnetic field.

This phenomenon is known as "Hall effect" and generated voltage is called Hall "voltage"

### Hall Effect in n-type Semiconductor & P-type



Consider n-type semiconductor in the form of rectangular slab. Current ( $I$ ) flow in  $x$ -direction magnetic field ( $B$ ) is applied in  $z$ -direction. Due to Hall effect Voltage developed along  $y$ -direction (in fig). current flow due to electron flow.

Electrons moving with velocity ' $v$ ', experience downward force.

Force due to magnetic field (Downward) } =  $Bev$  —①

Force due to potential difference } =  $eE_H$  —②

At equilibrium  $\text{①} = \text{②}$

$$Bev = eE_H$$

$$E_H = Bv —③$$

We know that

Current density

$$J_x = -nev$$

$$\theta = \frac{-J_x}{ne} —④$$

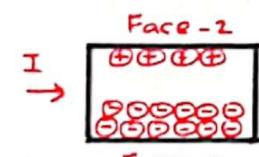
Substitute eqn ④ in eqn ③

$$E_H = B\left(-\frac{J_x}{ne}\right)$$

$$E_H = R_H J_x B —⑤$$

$\therefore$  Hall coefficient

$$R_H = \frac{E_H}{J_x B}$$



where  $R_H = \frac{-1}{ne}$   
-ve sign indicates  
Elec field in -ve  
Y axis

III<sup>ly</sup> in P-type Semiconductor  
Current flow due to flow of holes  
(+ve charge)

Compare with n-type Semiconductor  
current density  $J_x + Pev$

$$\theta = \frac{J_x}{Pe} —⑥$$

Substitute eqn ⑥ in ③

$$E_H = R_H J_x B —⑦$$

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



Face-1

Hall coefficient in terms of Hall voltage

$$\text{Hall voltage } V_H = E_H t —⑧$$

where  $E_H \rightarrow$  Hall field.

Substitute eqn ⑦ in eqn ⑧

$$V_H = R_H J_x B t —⑨$$

Area of the Sample  $A = \text{thickness} \times \text{breadth}$   
 $A = bt$

$$\text{current density } J_x = \frac{I_x}{A}$$

$$J_x = \frac{I_x}{bt} —⑩$$

Substitute eqn ⑩ in eqn ⑨

$$V_H = \frac{R_H I_x B t}{bt}$$

$$V_H = \frac{R_H I_x B}{b} —⑪$$

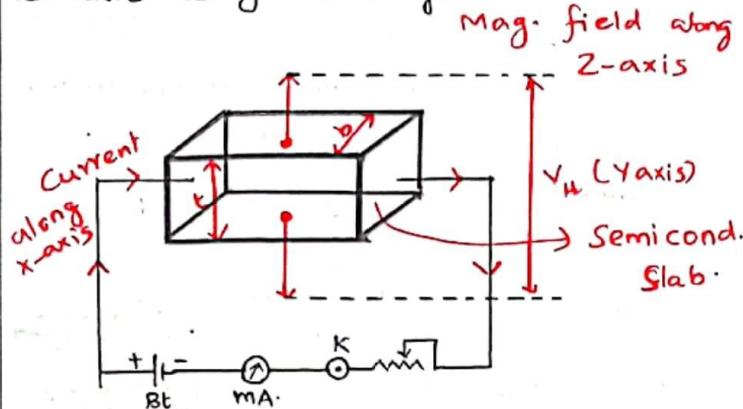
$$R_H = \frac{V_H b}{R_H B} —⑫$$

Eqn ⑫ gives hall coefficient in terms of hall voltage.

Experimental Determination of Hall Coefficient

A semiconductor slab of thickness 't' and breadth 'b' is

taken and current is passed through x-axis using battery.



The slab is placed between poles of an electromagnet. Magnetic field is applied along z-axis. The Hall voltage ( $V_H$ ) is measured by placing two probes at the centre of the top and bottom of the slab.

By measuring Hall voltage, Hall coefficient is determined from the formula

$$R_H = \frac{V_H b}{I x B}$$

### Mobility of charge Carriers:

We know that, Hall coefficient

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

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

For n-type Semiconductor

$$R_H = -\frac{1.18}{ne}$$

$$ne = -\frac{1.18}{R_H} \quad \text{---(1)}$$

For p-type Semiconductor

$$R_H = \frac{1.18}{pe} \quad pe = \frac{1.18}{R_H} \quad \text{---(2)}$$

### Electrical conductivity

for n-type Semiconductor

$$\sigma_e = ne \mu_e \quad \text{---(3)}$$

$$\text{---(1)} \Rightarrow \mu_e = \frac{\sigma_e}{-1.18 R_H}$$

$$\mu_e = -\frac{\sigma_e R_H}{1.18} \quad \text{---(4)}$$

For p-type Semiconductor

$$\sigma_h = pe \mu_h \quad \text{---(5)}$$

$$\text{---(2)} \Rightarrow \mu_h = \frac{\sigma_h}{1.18 R_H}$$

$$\mu_h = \frac{\sigma_h R_H}{1.18} \quad \text{---(6)}$$

### Application of Hall Effect:-

(i) Used to determine whether the material is p-type or n-type Semiconductor.

(ii) Used to find the carrier.

Concentration

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

(iii) used to find the mobility of Charge carriers

$$\mu_e = \sigma_e R_H, \mu_h = \sigma_h R_H$$

### Schottky Diode:-

Schottky diode is a unilateral device, in which current flow from metal to semiconductor in one direction.

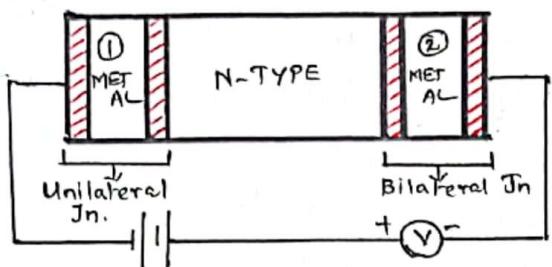


### Construction:

A Schottky diode also called as Schottky barrier diode.

It is made up of 2 junctions.

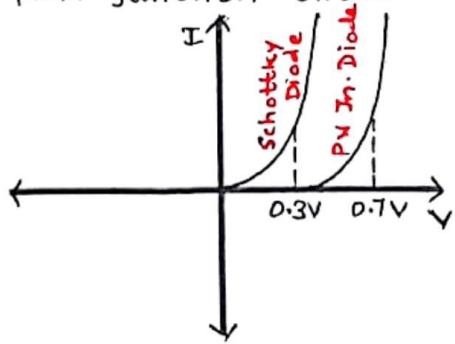
- (i) Unilateral [Metal-Semiconductor]  
(ii) Bilateral [Metal-Semiconductor]



The Schottky diode act as a terminal device in which metal 1 and Semiconductor formed at one end act as anode with unilateral function, metal 2 and Semiconductor formed at other end act as cathode with bilateral function.

### Working:

Applying forward bias, the voltage applied to diode and their corresponding current is measured. The V-I curve is drawn for Schottky diode as compared with P-N Junction diode.



As per V-I curve, during forward bias for a Schottky diode I increase enormously even for

small applied V, due to 3 component of current occurs in Schottky diode

### Application:

- \* Due to low voltage drop, they are used in high switching system
- \* They are used in BJT
- \* It is used in Radio frequency application.
- \* It is used in high power supply

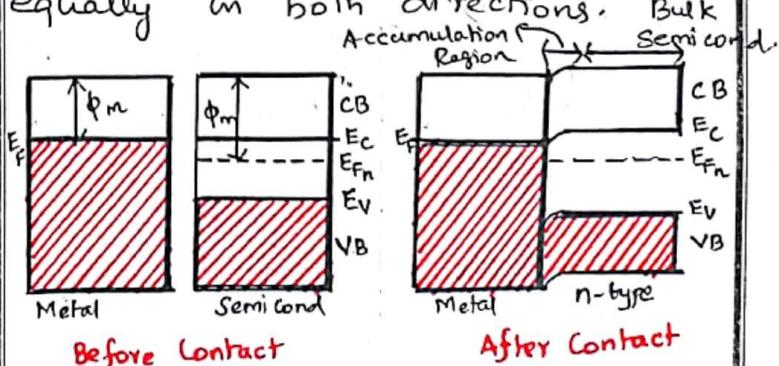
### Ohmic Contacts:

#### Definition:

An ohmic contact is a type of metal Semiconductor junction. It is formed by a contact of a metal with a heavily doped Semiconductor.

When the Semiconductor has a higher work function than that of metal, then the junction formed is called the ohmic junction.

Here the current is conducted equally in both directions.



**Working:**

Fermi levels of the metal and Semiconductor are at different positions before contact. (Fig (i))

After contact, at equilibrium the electrons move from the metal to the empty states in the conduction band of Semiconductor.

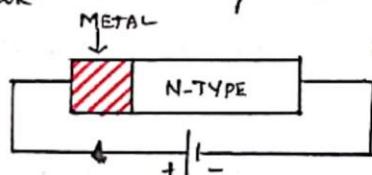
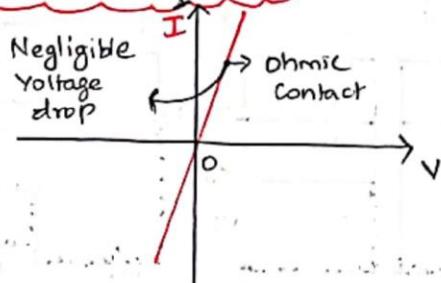
∴ An accumulation region near the interface is appeared. (Semiconductor side)

Fermi levels after contact are shown in [fig(ii)].

Accumulation region has a higher conductivity than the bulk semiconductor due to higher concentration.

Ohmic contact behaves as a resistor conducting in both forward and reverse bias. (Fig. (iii)).

The resistivity is determined by the bulk resistivity of the Semiconductor.

**V-I characteristics:**

The current density is proportional to the potential across the junction.

Ohmic contacts are non-rectifying and show negligible voltage drop and resistance irrespective of the direction and magnitude of current.

**Applications:**

The use of ohmic contact is to connect one semiconductor device to another, an IC or to connect an IC to its external terminals

## DOMAIN THEORY OF FERROMAGNETISM

It is used to explain the properties of ferromagnetic material.

The material shows permanent magnetisation is called "Ferromagnetic" materials.

It consists of large number of dipoles align themselves in small region called "domain", wall that separate two domain is known as domain wall.

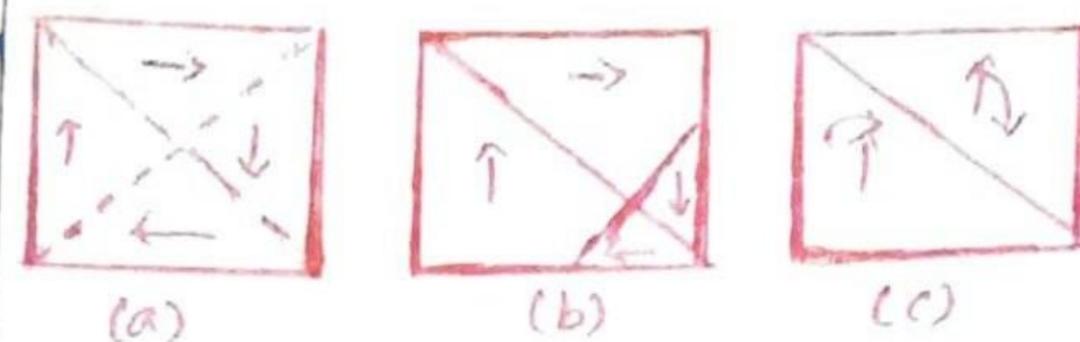
Domain varies in size from  $10^{-6}$  to entire dimension. The direction of dipole inside the domain is parallel.

In the presence of external field the magnetization occurs by

- \* Movement of domain wall
- \* Rotation of Domain wall

By the movement of domain wall when small field (weak field) is applied the domains favourably align to the field "grow" in size is known as "Domain growth". Due to this

Domain walls are displaced outward.



- (a) Random domain alignment
- (b) Domain growth
- (c) Domain Rotation.

By rotation of domains walls:

When the strong field is applied, movement of domain wall is permanent and the dipoles tend to rotate towards the external field direction.

Hence in the strong field region magnetisation is due to the rotation of domain in the ferromagnetic material.

Types of energy:

Four type of energy involved in domain growth. The total energy of the domain comprise the sum of following energies.

- i) Exchange energy
- ii) Crystal Anisotropy energy
- iii) Domain wall energy
- iv) Magneto-strictive energy.

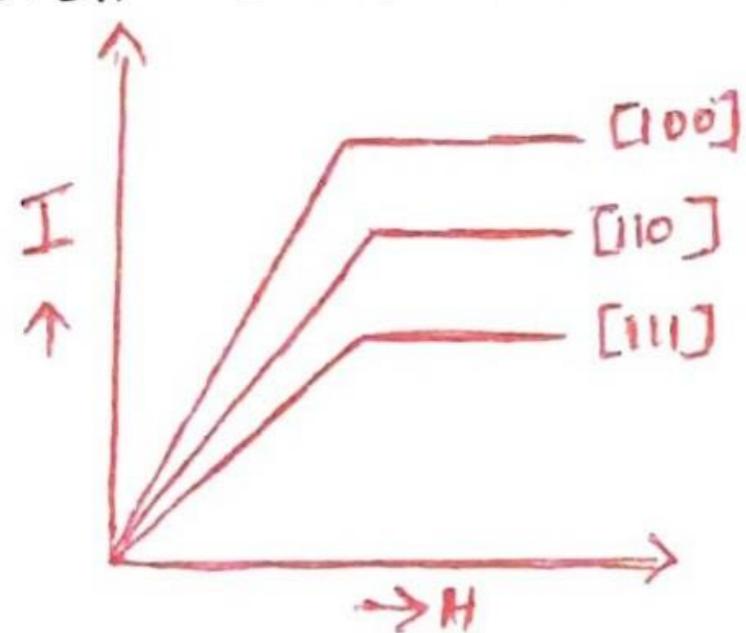
(i) Exchange energy:

It is defined as the energy required to align the atomic magnets in to a single domain.

It arises from the interaction of the electron spin, it is also called as Magnetic field energy.

### ii) Crystal anisotropy energy:-

It is the excess energy required to magnetise the material in its easy direction with less field.



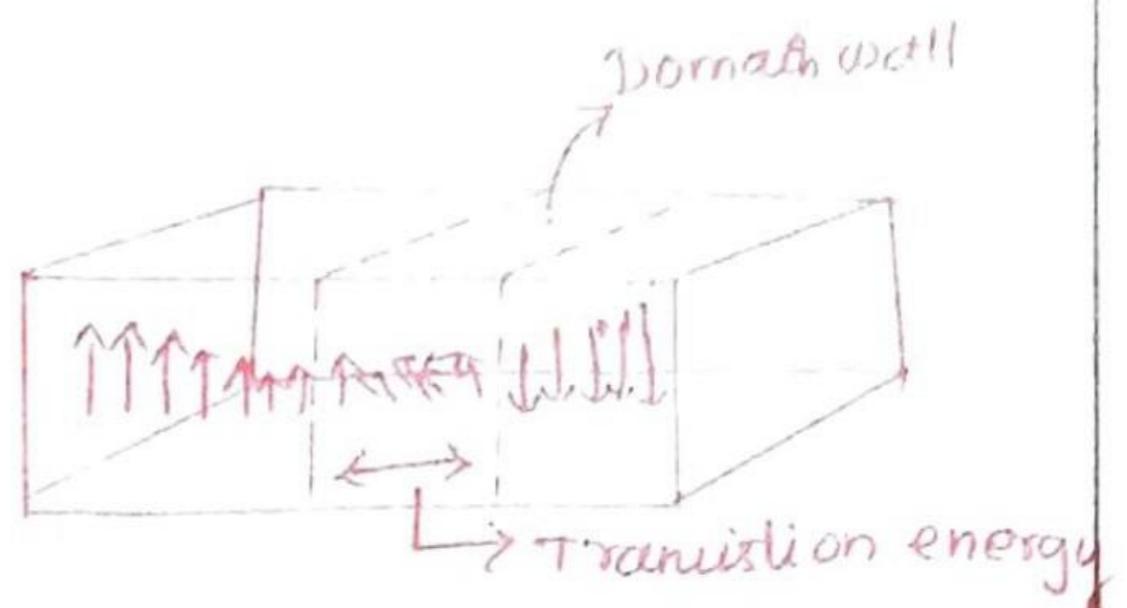
For example in iron easy direction is [100], medium direction is [110] and the hard direction is [111].

### iii) Domain wall energy:

It is a transition layer which separates the adjacent domains, magnetised in different directions. Based on spin alignments, two types of Bloch walls may arise, namely

i) Thick wall

ii) Thin wall.



#### i) Thick wall:

when the spins at the boundary are misaligned and if the direction of the spin changes gradually. It leads to a thick Bloch wall.

#### ii) Thin wall:

when the spins at the boundaries changes abruptly, then the anisotropic energy becomes very less. It leads to a thin Bloch wall.

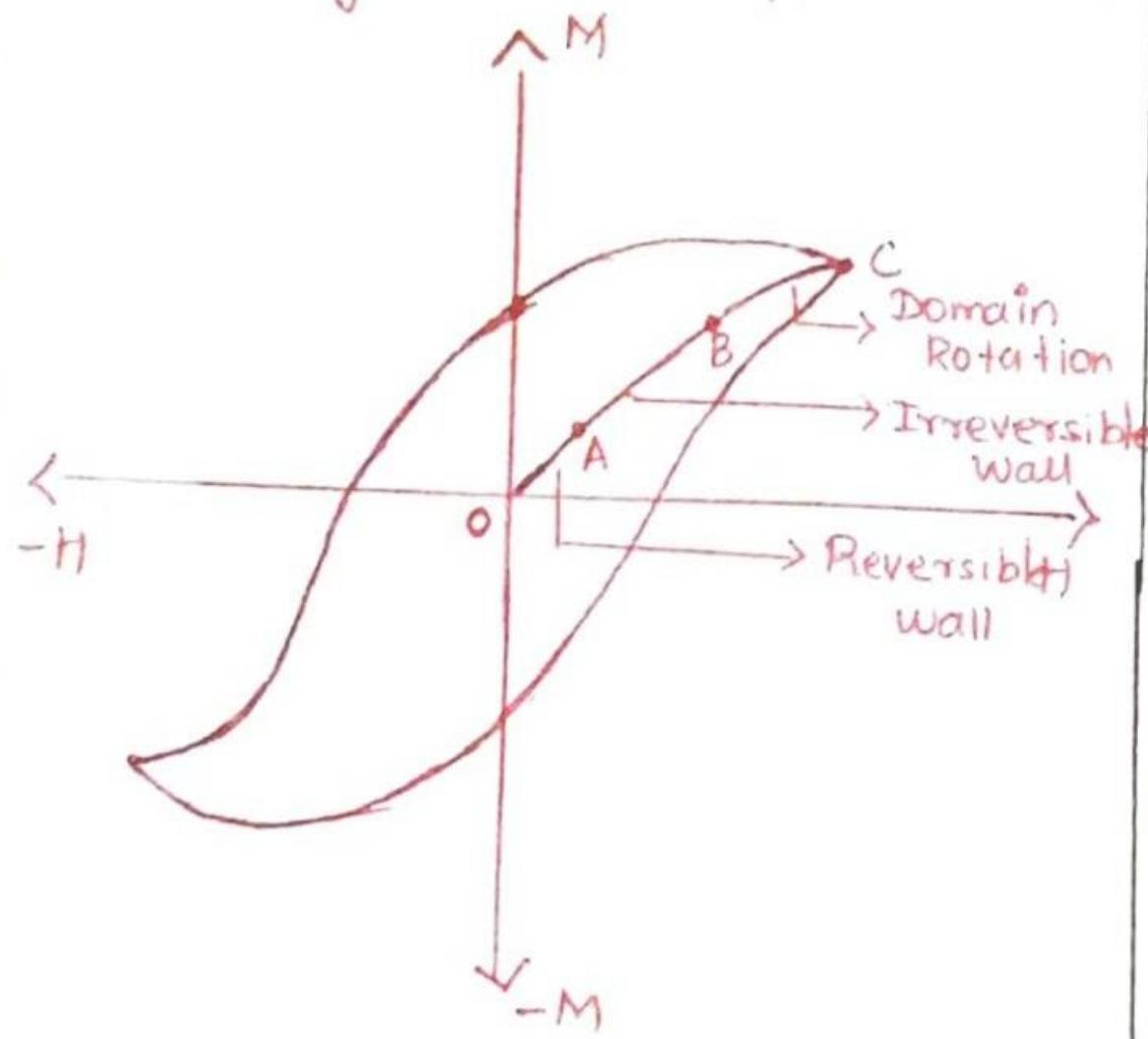
### iv) Magneto-strictive energy:

The change in dimension of ferromagnetic material when it is magnetized is known as "magnetostriiction".

In ferromagnetic material during magnetisation domains parallel to the external field direction grow inside and the domains in other direction decrease in size. The crystal lattice strain associated with magnetostriiction is known as "Magnetostriiction energy".

## Hysteresis - M vs H Behaviour:- 'domains'.

The lagging of magnetisation behind the magnetising field is, when a ferromagnetic material is made to undergo through a cycle of magnetisation, the variation of  $M$  with respect to  $H$  can be represented by a closed hysteresis loop (or) curve.



When the ferromagnetic material is subjected to external field, there is an increase in the value of resultant magnetic moment due to two process,

- i) Movement of domain walls
- ii) Rotation of domain walls.

If the applied field is removed, then the domain returns to its original state, and is known as <sup>(OA)</sup> reversible

Now, even when the field is removed, because of the displacement of domain wall to a very large distance. The domain boundaries do not come back to their original position (AB) and this domains are called "irreversible domains".

Now, when the field is further increased, the domains start rotating along the field direction and the anisotropy energy is stored in the hard direction (BC).

### Removal of field:-

On the removal of the field ' $H$ ' value reduced to zero but still material possess magnetisation.

The negative field (reverse magnetic field) that supplied to reduce the magnetisation of the specimen is zero is called "Coercivity". The amount of energy spent is loss, hence in complete cycle of magnetisation, we obtain a curve known as 'hysteresis loop'

and the area covered by the hysteresis loop represent the loss of energy. It is in the form of heat & known as **hysteresis loss**. After attains maximum magnetisation even after the removal of external field the material possess magnetisation called as **Remanentivity**.

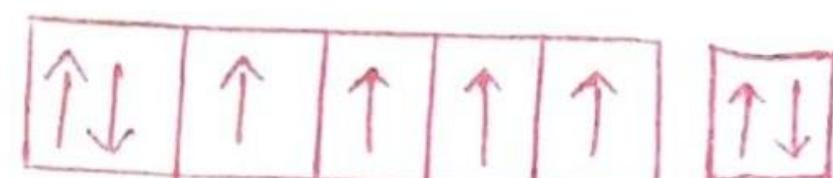
### Exchange interaction:

The ferromagnetic property is exhibited by transition elements such as iron, cobalt and nickel at room temperature and rare earth elements like gadolinium and dysprosium.

The ferromagnetic materials possess parallel alignment of dipoles. The electronic configuration of iron is  $1s^2, 2s^2, 2p^6, 3s^2, 3p^6, 3d^6, 4s^2$ . For iron, the 3d subshell is an unfilled one. This 3d subshell have five orbitals.

For iron, the six electrons present in the 3d subshell occupy the orbitals such that there are four unpaired electrons

and paired electrons.



3d orbital      4s orbital

The parallel alignment of dipoles in iron is not due to the magnetic interaction. It is due to the pauli's exclusion principle and electrostatic interaction energy.

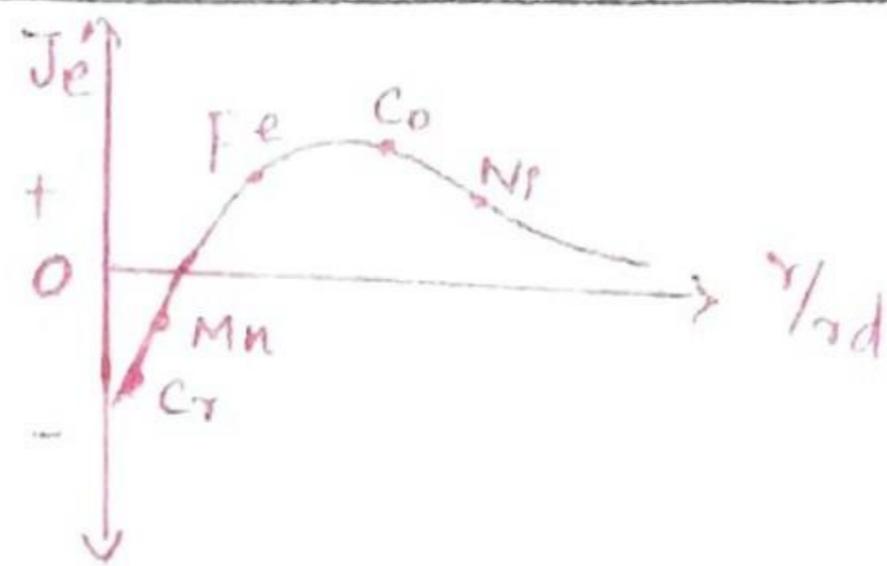
The pauli's exclusion principle and electrostatic interaction energy are combined together and constitute a new kind of interaction known as **exchange interaction**.

The exchange interaction between any two atoms depends upon the interatomic separation between the two interacting atoms. The exchange interaction between any two atoms is given by

$$E_{ex} = -J_e S_1 S_2$$

where  $J_e$  is the numerical value of the exchange integral,  $S_1$  and  $S_2$  are the spin angular momenta of 1<sup>st</sup> and 2<sup>nd</sup> electron.

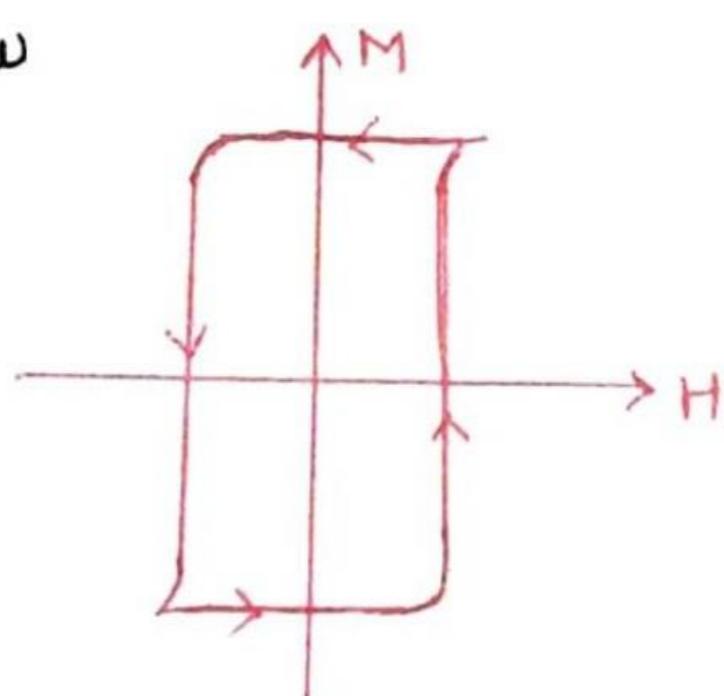
The exchange integral value is negative for a number of elements. Therefore, Exchange energy value is negative when the spin angular momentum  $s_1$  and  $s_2$  are opposite direction. Antiparallel alignment of dipole is favoured. In some materials like Iron, Cobalt and nickel the exchange integral value is positive. This will produce a parallel alignment of dipoles.



The positive value of exchange integral represents the material is ferromagnetic and the negative exchange integral value represents the material is antiferromagnetic.

### Soft Magnetic Material

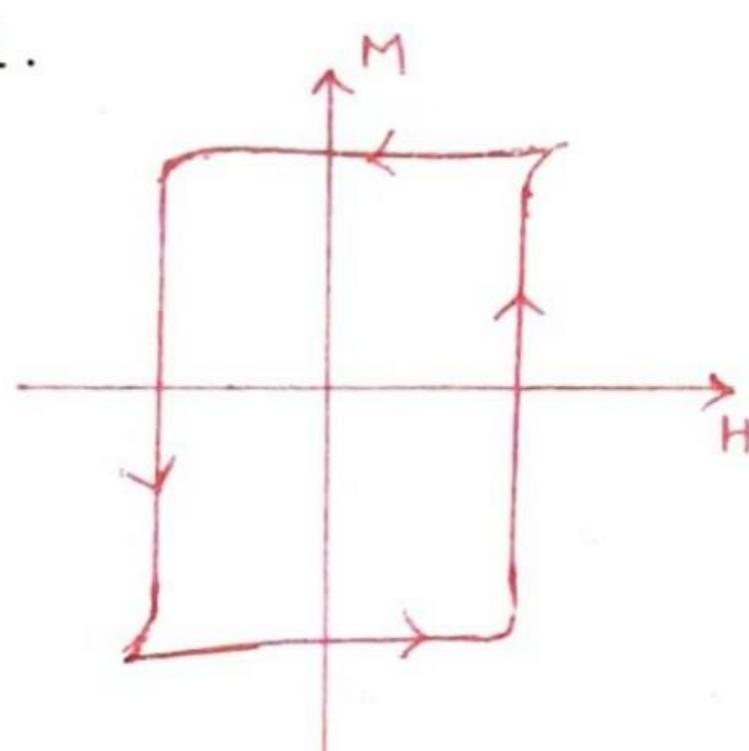
1. They can be easily magnetised and demagnetised
2. The Hysteresis loop is very narrow



3. Hysteresis loss is very small
4. Permeability and susceptibility are very large.

### Hard Magnetic Material.

1. They cannot be easily magnetised and demagnetised.
2. The Hysteresis loop is very broad.



3. Hysteresis loss is very high
4. Permeability and susceptibility are very small.

### Soft Magnetic Material

5. Retentivity and coercitivity are small.
6. Movement of domain wall is easy.
7. They have low eddy current loss.
8. These materials are free from irregularities like impurities.
9. Examples: Iron, silicon alloys, Ferrites
10. It is used to make the temporary magnets. They are also used in switching devices, electro magnets etc.,

### Hard Magnetic Material

5. Retentivity and coercitivity are large.
6. Movement of domain wall is not easy.
7. They have high eddy current loss.
8. These materials have large amount of impurities.
9. Examples: carbon steel, tungsten steel, chromium steel.
10. It is used to make the permanent magnets which is used in magnetic detectors, microphones etc.,

## Magnetic Hard disk drive

(HDD) with GMR sensor:-

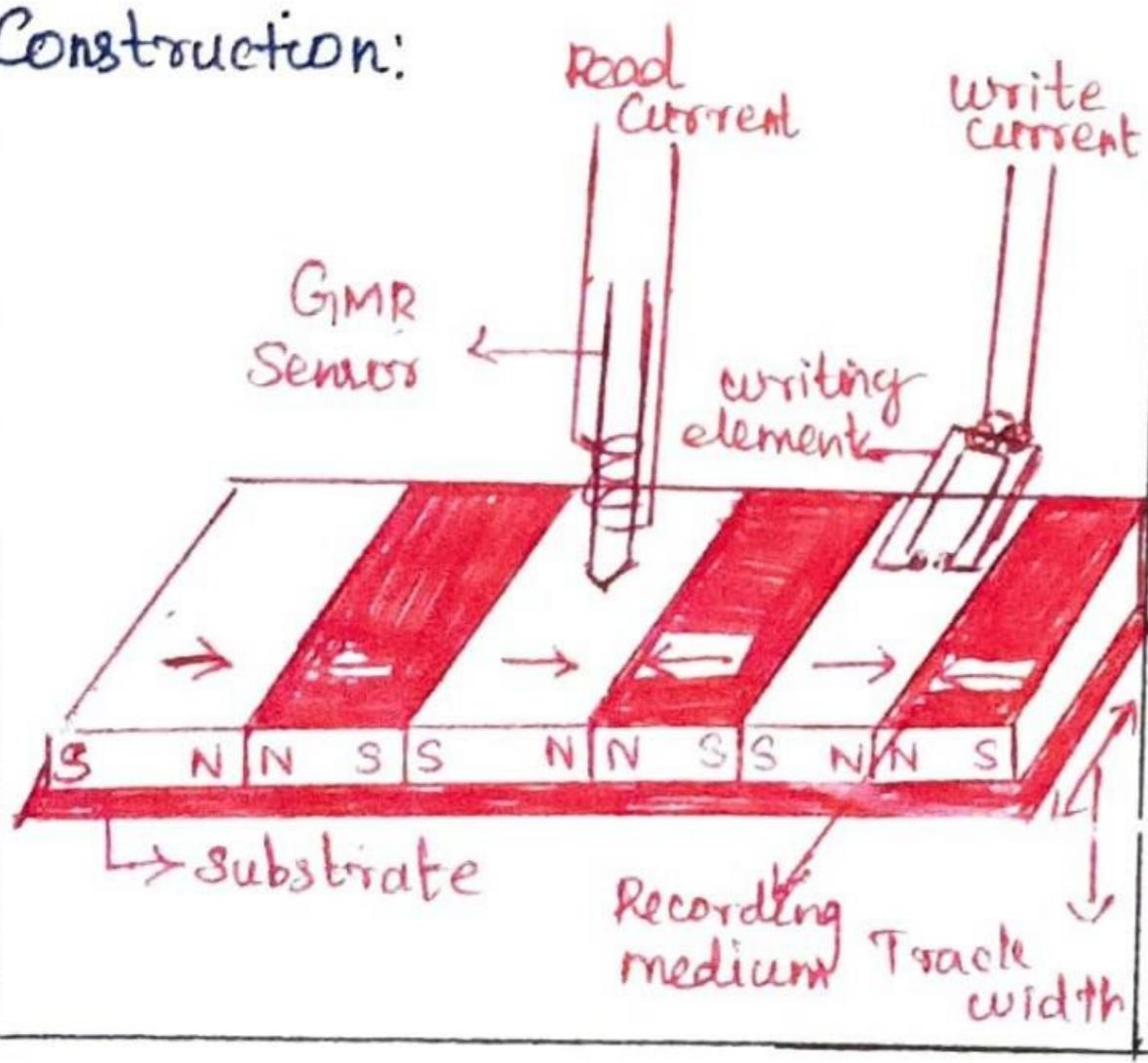
Hard disk drives (HDD) made up of magnetic garnet materials are called magnetic hard disk drives.

GMR (Giant Magneto Resistive) Sensors, which has a very high magnetic sensitivity are used to read the data at greater speed.

Principle:

In Hard disk drives, the binary data in terms of zero's and one's are stored by inducing magnetic moment in a thin magnetic layer and GMR effect is used as the principle to read the data in HDD.

Construction:



- \* Recording medium made up of thin layer of magnetic garnets grown over the substrate.
- \* The GMR sensor, which is made up of ferrites and anti-ferromagnetic materials.
- \* The writing element is made up of inductive magnetic transducer.
- \* The writing element and the GMR sensor made to slide over the recording media in the longitudinal direction. Hence this method is called as longitudinal recording.

Working:-

Writing / storing:

- \* Initially the current is passed through the writing element, magnetic field is induced in between the gap.
- \* During writing, the current is kept constant and direction of current is reversed.
- \* When the induced magnetic field is greater than the coercivity of the recording media, then data is recorded in the form of 1.

\* Here zero (0) represents missing transition and one (1) represents transition in the medium.

\* Thus one (1) is stored as data in the recording medium as a magnetic transition.

\* When there is no magnetic transition, then it is referred as zero (0).

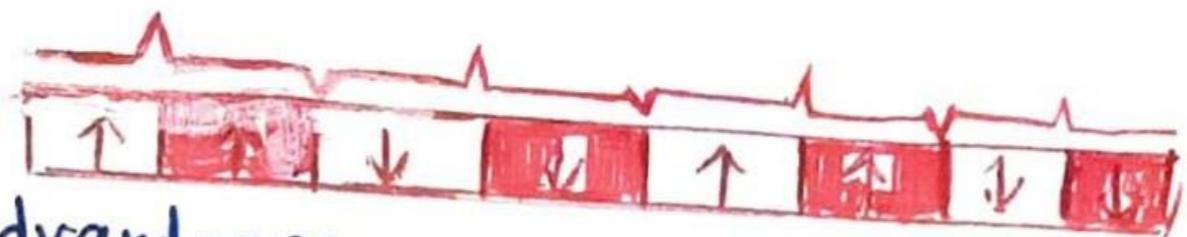
#### Reading:-

\* GMR effect is the principle used to read the data from the recording medium.

\* When the GMR sensor is made to move near the recorded medium, then the resistance of the GMR sensor varies, with respect to the orientation of the magnetic moments.

\* When the layers are magnetised in parallel manner, then the resistance is minimum, therefore maximum current flows

through the sensor, represents the data as one (1).  
\* When the layers are magnetised in antiparallel manner, then resistance is maximum, therefore minimum current flows through the sensor, represents the data as zero (0).



#### Advantages:

\* It has very large storage capacity.

\* It is compact in size.

\* GMR sensor are very sensitive in reading.

#### Disadvantages:

\* HDD has bulkier form factor.

\* They consume more power and will damage.

\* The GMR noise ratio is high.

\* Sometimes the data in HDD may be corrupted, due to thermal radiation.

#### Application:

\* HDD's are used as storage devices.

\* They are used in coding.

\* It is used in many engineering fields such as nanoelectronics.

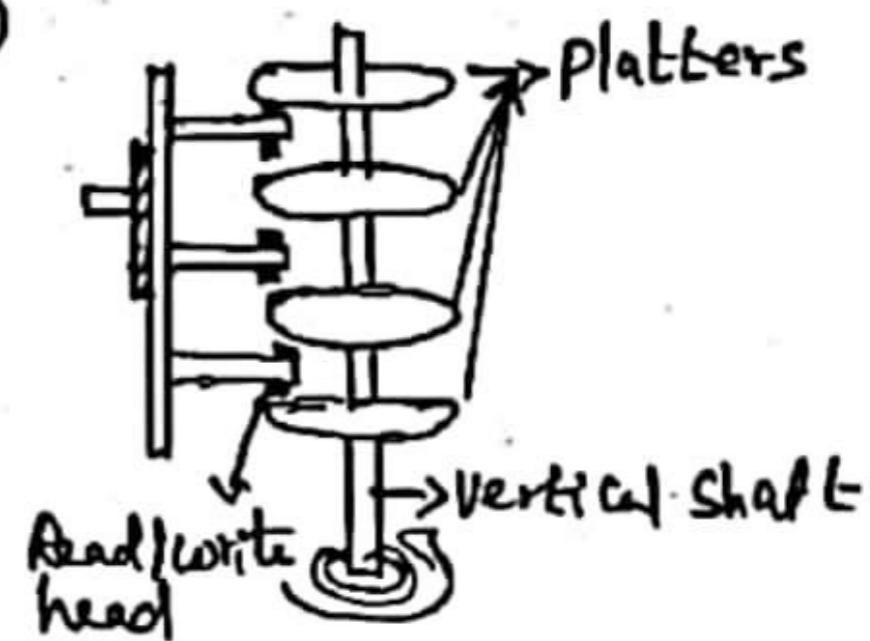
## MAGNETIC PRINCIPLE IN COMPUTER DATA STORAGE

- (i) Storage devices are used to store in (or) retrieved data from it.
- (ii) Generally Ferro(or) Ferrimagnetic materials are used in the storage devices. Since magnetisation is large with small magnetic field.
- (iii) Magnetic Recording heads are the main part of the storage device.
- (iv) It is working under the principle of "Magnetic Induction".
- (v) The recording of digital data depends upon the direction of magnetisation.
- (vi) Soft magnetic materials used in temporary storage.
- (vii) Hard materials used in permanent storage devices.
- (viii) Magnetic medium is made up of magnetic material deposited on thin plastic.

## STORAGE DEVICE - MAG. HARD DISC

- (1) They are called "direct access storage" devices.
- (2) Coated with magnetic material.
- (3) It is made up of "Hard aluminium platters".
- (4) The surface of platter is well machined.
- (5) It is built into a box consisting number of disc mounted in a vertical shaft.

- (b) The disc pack is placed in a drive mechanism called "Hard disc drive".
- (1) A read and write head in the sensing arm used to store & retrieve data.
- (2) Arms are moving in & out between the platters does not touches the surface.
- (3) Giant magneto Resistance Sensors (GMR) used as a sensing element.
- (4) When it is made to move near the recorded medium the resistance of the GMR sensor varies.
- (5) When the layers are magnetized in parallel manner Resistance is minimum - Current flows maximum.
- (6) If the magnetisation is antiparallel resistance maximum, current flows minimum (o)



### Advantage:-

- \* Large storage capacity.
- \* Thousands of files can be stored permanently.
- \* High speed in reading/writing.
- \* Protected from outer disturbance.

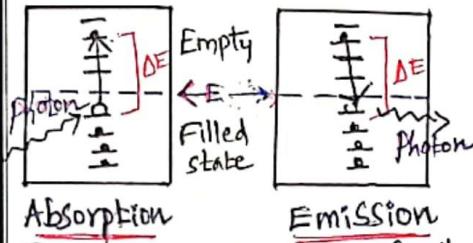
### Disadvantages:-

- \* Very costly.
- \* If the data corrupted heavy loss data.
- \* GMR are temperature dependent.

## ABSORPTION, EMISSION AND SCATTERING OF LIGHTS IN

**METAL**

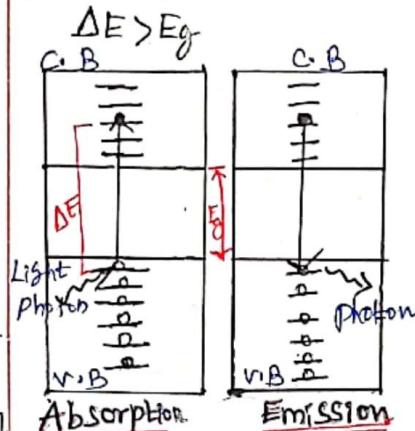
- ① Metals are opaque.
- ② In which Incident light absorbed by the free electrons.
- ③ Absorption is within a very thin outer layer less than  $0.1\text{ }\mu\text{m}$ .
- ④ All frequencies of light absorbed by metals.



- ⑤ Metals are opaque for the EM radiation of lower frequency [Visible, IR, UV etc.]
- ⑥ For higher frequencies [X-rays & γ-rays], it is transparent.
- ⑦ The absorbed ray reemitted from the surface with same wavelength known as reflected ray.
- ⑧ Reflectivity 0.9-0.95
- ⑨ Fraction of the energy dissipated as heat.
- ⑩ Colour of the metal defined by wavelength distribution of the reflected radiation.

**INSULATOR**

- DIELECTRIC**
- ① Absorption occurs during light interaction.
  - ② Electron excited to conduction band from valence band.
  - ③ holes are generated.
  - ④ This excitation is possible, when  $\Delta E > E_g$



$$\hbar\nu > E_g \text{, where } \frac{\hbar c}{\lambda} > E_g \quad [\nu = c/\lambda]$$

$\hbar$  - Planck's constant.

$\lambda$  - wavelength.

$\nu$  - frequency.

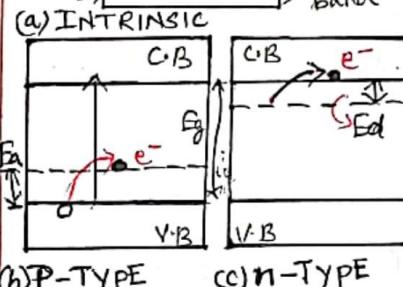
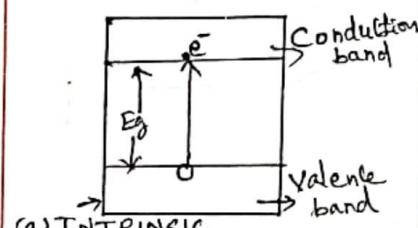
$$E_{g(\max)} = \frac{hc}{\lambda_{\min}} = \frac{6.624 \times 10^{-34} \times 3 \times 10^8}{0.4 \times 10^{-6}} = \frac{4.96 \times 10^{-19}}{1.6 \times 10^{-19}}$$

$$E_{g(\max)} = \pm 3.1\text{ eV}$$

Thus absorption Energy should be greater than 3.1 eV.

**SEMICONDUCTOR**

- ① In semiconductors, photon absorption creates holes in several ways.
- ② The electron crosses the energy gap and excited to higher energy level.
- ③ This excitation is possible only when the energy of the photons,  $E > E_g$ .



$$\hbar\nu > E_g$$

$\hbar$  - Planck's constant  
 $\nu$  - frequency of photon

$$\frac{hc}{\lambda} > E_g$$

Here  $\lambda_{\max}$  is  $0.7\text{ }\mu\text{m}$

$$\text{Then, } E_g = \frac{2.84 \times 10^{-19}}{1.6 \times 10^{-19}}$$

$$E_g = 1.8\text{ eV}$$

Result indicates absorption possible within 1.8 eV Bandgap.

PHOTO CURRENT IN PN DIODEDefinition:-

It is a reverse bias P-n Junction Diode which responds to light absorption.

Principle:-

When a light is incident on Junction region under reverse biasing electron and holes increases, thereby Reverse saturation current increased.

DIODE SYMBOL:-CONSTRUCTION:-

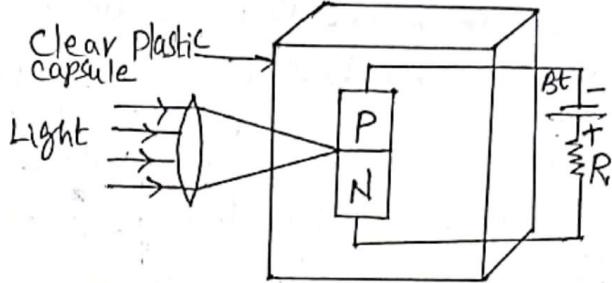
It consists of a P-n junction placed inside transparent plastic capsule.

WORKING:-

- 1) When the Reverse Voltage is applied under dark condition.
- 2) Then a Constant Current independent of Reverse bias Voltage is obtained.
- 3) The reverse saturation current is due to thermally generated minority charge carriers. It is called dark current ( $I_d$ ).
- 4) It is proportional to the Concentrations of Minority Carriers.
- 5) When the light falls on the diode surface, additional

electron-hole pairs are generated.

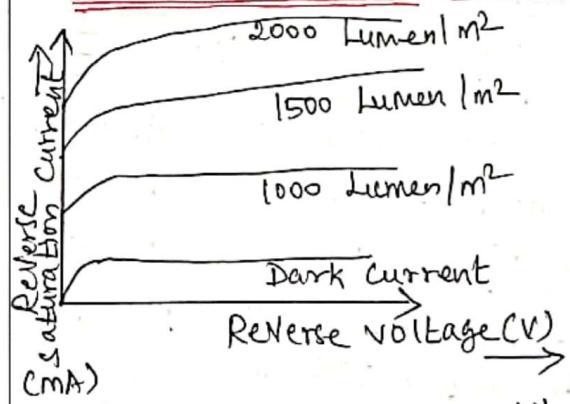
- 6) These injected minority carriers diffuse to junction and contribute to the additional current.



- 7) Total Reverse current,

$$I = I_s + I_d$$

$I_s$  - short circuit current is proportional to the intensity of light.

V-I characteristics Curve:-

- ii) The current increases with increase in the level of illumination for a given reverse voltage.

APPLICATIONS:-

- 1) High-speed reading of Computer punched Cards & Tapes.
- 2) Light sensor & Light operated switches.
- 3) Reading of sound track in film.
- 4) Variable resistance derived controlled by light intensity.

## UNIT-IV OPTICAL PROPERTIES OF MATERIALS

PH3256-PHYSICS FOR INFORMATION SCIENCE

### Advantages of PN Diode:-

- (1) Compact (2) Noise-Less
- (3) Light weight (4) Long-Life
- (5) Rugged Mechanically.

### Disadvantages of PN Diode:-

- (1) Dark current is temperature dependent.
- (2) Thermal stability is poor.
- (3) Amplification Compulsorily
- (4) Efficiency is poor in winter season.



### Definition:-

It is a PN junction diode which converts Solar energy (Light energy) into electrical energy.

Common material used is Si, GaAs, InAs, CdAs.

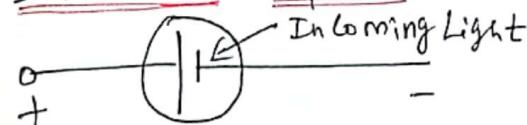
Bandgap of Si is 1.12 eV

### Principle:-

When Light reaches the P-n junction, the Light photons can easily enter in the junction through very thin p-type layer.

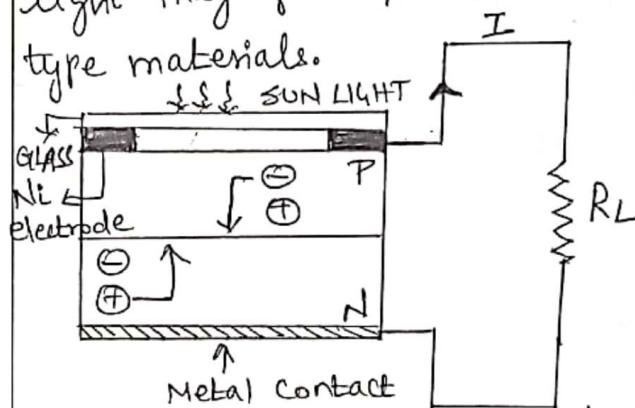
It supplies sufficient energy to the junction to create a number of electron-hole pairs.

### SOLAR CELL SYMBOL:-



### CONSTRUCTION:-

- 1) The p-n diode is made up of silicon packed in a can with glass window on top such that light may fall upon p and n type materials.



- 2) Nickel ring at the top and a metal at bottom act as terminals.
- 3) Very thin p-n layers formed as a junction.

- 4) Above (N) ring a transparent glass plate is placed.

- 5) Load Resistance  $R_L$  is connected between the terminal parts.

### WORKING:-

\* The light incident through the glass plate leads to breakage of Covalent bond.

\* Due to this electron and hole pair is produced.

\* Here electron & hole diffuse to the junction even before it recombines.

- \* The minority charge carrier reaches the other end. This flow is the reason for the minority current.
- \* Minority current is directly proportional to the intensity of light.

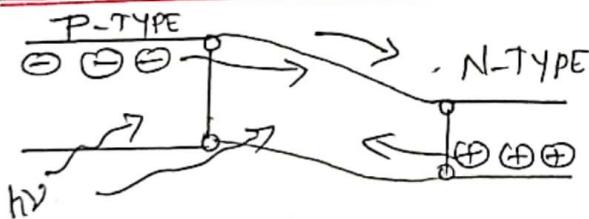


\* It is open circuited now. So, that the accumulated electron-hole gives rise to open circuit current ( $V_{oc}$ ).

\* By connecting load resistance reverse current flows through the circuit.

\*  $V_{oc}$  for a Si solar cell is 0.6 V +  $I_s$  (short circuit current) is 40 mA/cm<sup>2</sup> in (noon sunlight).

### ENERGY LEVEL DIAGRAM:-



### MERITS:-

- \* Utilize renewable energy
- \* Eco-friendly
- \* Highly efficient
- \* Pollution free
- \* Life time durability high.

### DEMERITS:-

- \* Cost is very high.
- \* Seasonal energy.
- \* Occupies more space.

### USES:-

- \* Power production.
- \* Used in satellite space probe.
- \* Power source in electrical & electronic devices.

## LED-LIGHT EMITTING DIODE

### Definition:-

It is a p-n junction diode which emits light when it is forward biased.



### Principle:-

Injection Luminescence is the principle used in LEDs.

The injection of electrons into the p-region from n-region makes a direct transition from conduction band to valence band. Then, the electrons recombines with holes & emit photons of energy Eg.

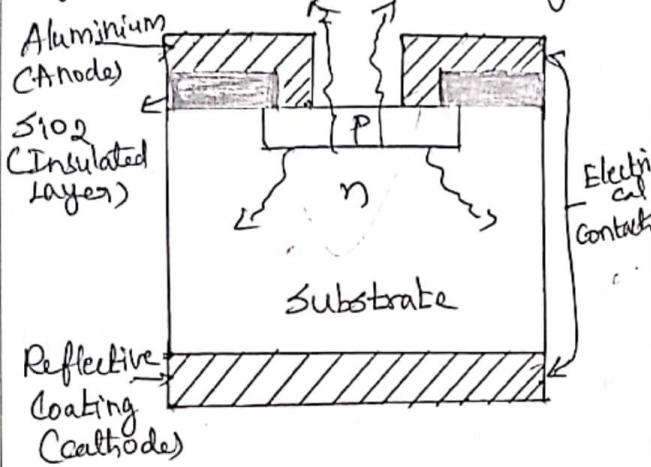
### CONSTRUCTION:-

- \* P-N junction is formed by diffusion technique by doping silicon with GaAs.

# UNIT IV OPTICAL PROPERTIES OF MATERIALS

PH3256-PHYSICS FOR INFORMATION SCIENCE

- \* Here, n-type layer is grown on substrate and a p-type layer is diffused in n-type.



- \* Carrier recombination is taken place in P-layer.

- \* Emission is increased by maintaining the thickness of 'P' layer smaller than 'n'.

- \* Top and bottom side Aluminium and gold, Coated as a thin layer acts as a electrode.

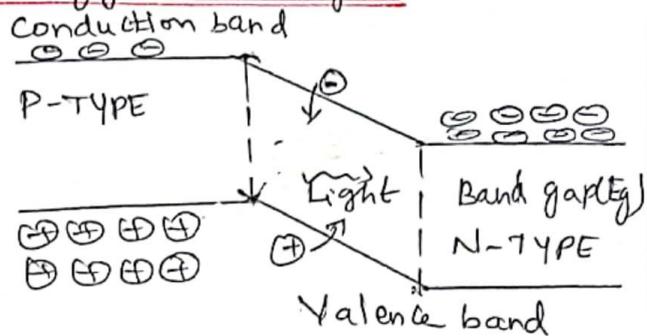
### Working:-

- \* When the biasing Voltage is applied due to forward biasing, the electron & holes from n-type & p-type materials injected into the junction.

- \* These are minority carriers in the other region.

- \* Therefore electron-hole recombination process occurs, thereby photon is emitted.

### Energy Level Diagram.



### Merits:-

- \* Smaller in size
- \* Cost is very low.
- \* Long life time.
- \* Different colour available
- \* Operates at very low voltage.
- \* Very fast response.

### Demerits:-

- \* Power output is low.
- \* Intensity is lesser than laser.
- \* Light cannot travel through longer distance.
- \* Less directional.

### Applications:-

- \* Used in display device.
- \* Used in indicators lamp
- \* Used in Burglar alarms.
- \* Used in pilot light.
- \* IR LEDs used in wire-less communication.

## OLED - Organic LED

### Definition:-

OLEDs are solid state devices made up of thin films of organic molecules that produce light with the application of electricity.

- \* It is also known as Light emitting polymers (LEP) or Organic Electro Luminescence (OEL)

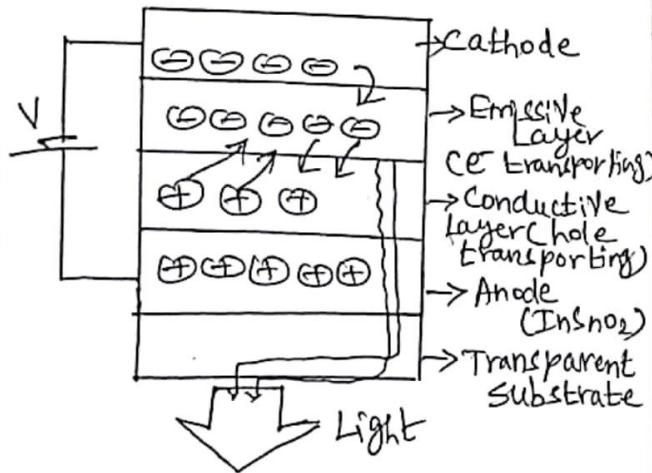
- \* Thickness of these layers is around 100-500 nm thick.

### Principle:-

An electron moves from the cathode to the emissive layer and the hole moves from the anode to the conductive layer and they recombine to produce photons.

### CONSTRUCTION:-

- \* It is constructed with different layers of polymers Coated with organic compound.



- \* It consists of an emissive layer made up of poly-fluorine and a conductive layer made up of poly-aniline kept between cathode and anode substrate.

- \* This whole layers placed over transparent electrode layers.

### WORKING:-

- \* Forward bias Voltage is applied across the OLED.

- \* Due to this cathode diffuse electron into emissive layer.

- \* Anode gets an electron from conductive layer & produces a hole in Conductive layer.

- \* Thus, emissive layer becomes rich in negative charged particles & conductive layer becomes rich in positive charged particles.

- \* Due to the electrostatic force, electrons and holes, come closer and recombine with each other.

- \* In organic SC, holes moves faster than electrons.

- \* This recombination produces light and it is emitted through the transparent substrate.

### MERITS:-

- \* It is thin & flexible.

- \* Light weight

- \* Larger field view.

## UNIT-IV OPTICAL PROPERTIES OF MATERIALS

PH250-PHYSICS FOR INFORMATION SCIENCE

- \* Emission is brighter than normal light (LED's).

### DEMERITS:-

- \* Manufacturing Cost is high.
- \* Easily damaged.
- \* Maintenance is high.

### APPLICATION:-

- \* Used in Cell phones, car radios, digital cameras.
- \* Used in TV screens, Computer displays, advertising.
- \* Automotive dash boards.
- \* Used in flexible display boards.

## LASER DIODES

### Definition:-

It is a specially fabricated P-n junction diode. This diode emits Laser Light when it is forward-biased.

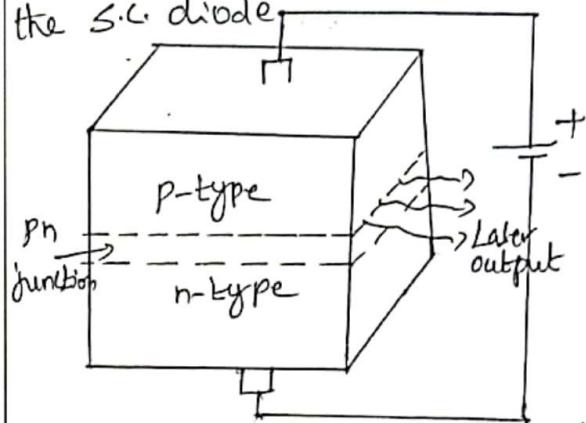
### PRINCIPLE:-

Recombination of electron-hole pair leads to emission of light in the forward biasing known as recombination radiation.

### CONSTRUCTION:-

- \* The active medium is a P-n junction diode made from a single crystal of GaAs.

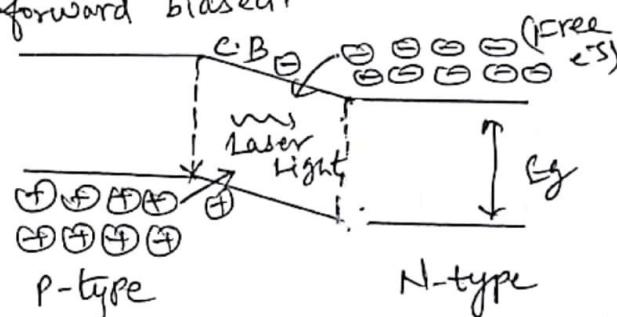
- \* The crystal is cut in the form of platelet (0.5 mm thickness) consists of two regions N-type & P-type.
- \* Metal electrodes are connected to both upper & lower surfaces of the S.C. diode.



- \* Forward bias voltage is applied through metal electrodes.
- \* The photon emission is stimulated in a very thin layer of pn junction.
- \* The end faces of the pn junction are well polished and parallel to each other.
- \* It acts as an optical resonator through which the emitted light comes out.

### WORKING:-

- \* When the pn-junction is forward biased,



- \* electrons & holes are injected into junction region.

\* The region around junction contains a large number of electrons in the Conduction band and holes in the Valence band.

\* During recombination, Light Photons are produced.

\* If the forward bias voltage is increased, more photons are emitted.

\* These photons trigger a chain of stimulated recombinations, more photons in phase travel forth & back by two polished surfaces of the junction.

\* After gaining enough strength, Laser beam of wavelength  $\lambda = 400 \text{ nm}$  is emitted from the junction.

$$E_g = \frac{hc}{\lambda}$$

#### MERITS :-

- \* Compact in size.
- \* High efficiency.
- \* Output power can be increased easily.
- \* Less power consumption.
- \* Waveform is Continuous / pulsed.

#### DEMERITS:-

- \* Output has large divergence.
- \* Poor Coherence & Monochromativity.

#### Applications of Laser diodes:-

- \* Used in optical Communication.
- \* Used in Barcode reader.
- \* Used in printing industry.
- \* Used as writing head in Disc drives.
- \* Used in Various Industrial applications such as cladding, welding, etc.

#### OPTICAL DATA STORAGE TECHNIQUES:-

Optical data storage is the storage of data on a optical medium using Laser Light.

These techniques have large storage capacities and two types of storage devices obtained.

- (i) Surface storage
- (ii) Volume storage

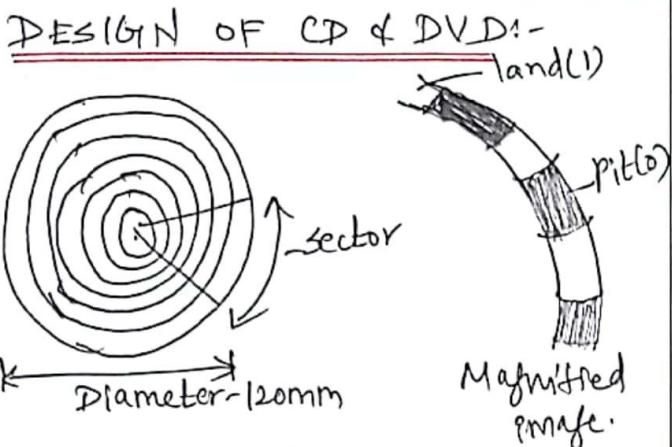
Surface storage is a familiar method in which data are stored in a compact disc contains optical coating.

#### Data storage:-

CD/DVD Coming under the category of a permanent optical storage device.

#### Principle:-

The reading & writing of data are done by forming pits (0's) & lands using low & high Power Laser beam.

CONSTRUCTION:-

- \* CD/DVD consists of a Plastic (or) photo polymer transparent disc substrate.
- \* Diameter of the disc 120mm and thickness is 1.2 mm.
- \* Substrate is Coated with Poly Carbonate.
- \* The reflectivity on the top surface is maintained by thin Vapour Coating of Aluminium (or) Silver.

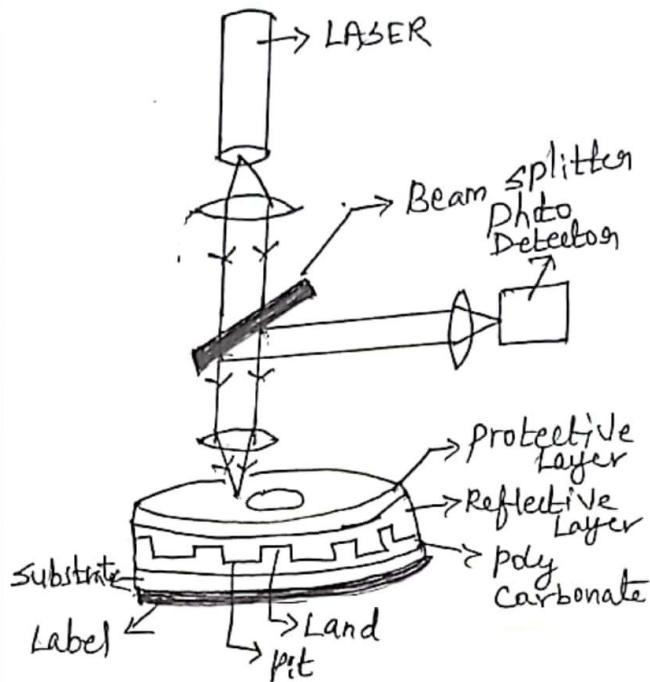
Storage Capacity:-

Depends on the no of sectors and the no of bytes it is varying.

Reading/Writing process:-Writing:-

- \* Initially CDs have high reflectivity to change it high power Laser is directed towards the land.

- \* This will burn the land and create pit (non-reflective hole).



- \* Remaining will be land portion with high reflectivity.

Reading:-

- \* For reading Low power Laser is focused on the track.
- \* The reflectivity varies here at lands and pits these reflections modulated in the form of 0's & 1's.
- \* These reflected signals focused on the photo diode through condensing lens by which it is demodulated & sent to o/p devices.

Uses:-

- \* Storage capacity high.
- \* All types of media file stored.
- \* Used to store software.
- \* Recovery is fast.
- \* Used to store data in any form.

S.No	TITLE	Description
1.	Type	: It is a heterojunction semiconductor laser
2.	Active medium	: PN junctions made from different layers.
3.	Pumping method	: Direct conversion method
4.	Power output	: The power output of laser beam is 1 mW
5.	Nature of the Output	: Continuous wave form
6.	Wavelength of the output	: Nearly $8000 \text{ } \text{\AA}$

### **Characteristics:Advantages:**

1. It produces continuous wave output.
2. The power output is very high.

### **Disadvantages:**

1. It is very difficult to grow different layers of PN junction.
2. The cost is very high.

### **Applications:**

- 1.This type of laser is mostly used in optical applications
2. It is widely used in computers, especially on CD-ROMs.

## **UNIT V**

### **NANO DEVICES**

#### **1. Write a note on quantum confinement**

Quantum confinement is change of electronic and optical properties when the material sampled is of sufficiently small size - typically 10 nanometers or less. The bandgap increases as the size of the nanostructure decreases.

Specifically, the phenomenon results from electrons and holes being squeezed into a dimension that approaches a critical quantum measurement, called the exciton Bohr radius.

The first experimental evidence of the quantum confinement effects in clusters came from crystalline CuCl clusters grown in silicate glasses

Spectroscopic studies on these clusters clearly indicated an up to 0.1 eV blueshift of the absorption spectrum relative to the bulk. In the case of CdS clusters, the absorption threshold is observed to blueshift by up to 1eV or more as the cluster size is decreased .

When the size of the cluster is smaller, its band gap is larger, consequently the first absorption peak is shifted closer to the blue.

## 2. Electron Tunneling:

Tunneling refers to the ability of using the quantum wave properties of an electron to allow transmission through a thin voltage-potential barrier. According to the laws of classical electrodynamics, no current can flow through an insulating barrier.

But quantum mechanics says that there is a finite probability for an electron on one side of the barrier to reach the other side. When a bias voltage is applied, there will be a current. This tunneling current will be proportional to the bias voltage. In electrical terms, the tunnel junction behaves as a resistor with a constant resistance.

An arrangement of two conductors with an insulating layer in between not only has a resistance, but also a finite capacitance. The insulator is also called dielectric in this context; the tunnel junction behaves as a capacitor.

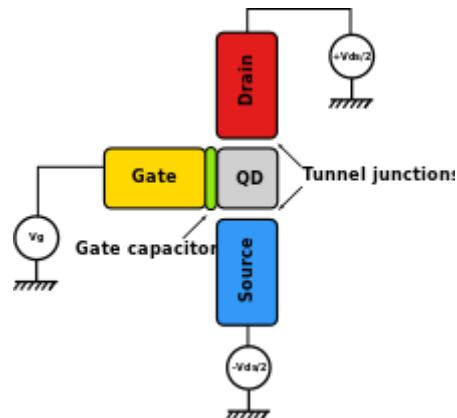
We know that for two conductors separated by an insulator, charge and voltage are proportional.  $Q = CV$

where  $Q$  is the charge on the conductors,  $C$  the capacitance and  $V$  is the voltage between the conductors.

## 3. Describe single electron transistor

### Single Electron Transistor:

These are devices operating at the quantum/nanoscale that have switching properties controlled by the removal or injection of a single electron; a device through which only one electron can be transported at a time.



A **single-electron transistor (SET)** is a sensitive electronic device based on the Coulomb blockade effect. In this device the electron flows through a tunnel junction between source/drain to a quantum dot (conductive island). Moreover, the electrical potential of the island can be tuned by a third electrode, known as the gate, which is capacitively coupled to the island. Fig. 1 shows the basic schematic of a SET device. The conductive island is sandwiched between two tunnel junctions,<sup>[1]</sup> which are modeled by a capacitance ( $C_D$  and  $C_S$ ) and a resistor ( $R_D$  and  $R_S$ ) in parallel.

A single-electron transistor is usually made by keeping two tunnel junctions in series. The transistor consists of a source electrode and a source drain, which is joined with the help of a tunneling island that is also capacitively connected to a gate. The electrons can travel to another electrode only through the insulator. There are two categories of single-electron transistors: metallic and semiconducting. The former makes use of a metallic island, and its electrodes using a shadow mask are mostly evaporated onto an insulator. The latter, in contrast, depends on severing the two-dimensional electron gas that forms at the interface of the semiconductors for the junction.

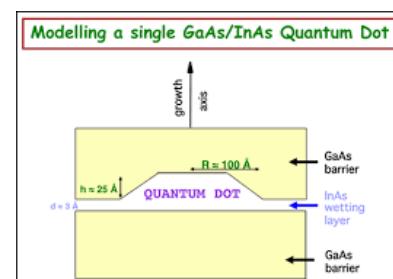
The resistance feature of a single-electron transistor depends on the size of the nanoparticles, capacitance and electron tunneling.

Single-electron transistors have many applications. They can be used as ultrasensitive microwave detectors and can also be used to detect infrared signals at room temperature. They are also efficient charge sensors capable of reading spin or charge qubits. Their high sensitivity feature allows them to be used as electrometers in experiments requiring high levels of specificity.

Single-electron transistors are not suitable, however, for complex circuits owing to the fluctuations present in them. Other limitations include randomness of the background charge and difficulty in maintaining the room temperature.

#### 4. Explain Quantum dot lasers with neat sketch

A **quantum dot laser** is a semiconductor laser that uses quantum dots as the active laser medium in its light emitting region. Due to the tight confinement of charge carriers in quantum dots, they exhibit an electronic structure similar to atoms.



Lasers fabricated from such an active media exhibit device performance that is closer to gas lasers, and avoid some of the negative aspects of device performance associated with traditional semiconductor lasers based on bulk or quantum well active media.

Improvements in modulation bandwidth, lasing threshold, relative intensity noise, linewidth enhancement factor and temperature insensitivity have all been observed.

The quantum dot active region may also be engineered to operate at different wavelengths by varying dot size and composition. This allows quantum dot lasers to be fabricated to operate at wavelengths previously not possible using semiconductor laser technology.

**The basic components of a laser** are

- An active medium (gain medium which is the QD in our case) where population inversion is created by a proper pumping mechanism. The spontaneously emitted photons at some site in the medium stimulate emission at other sites as it travels through it.
- An energy pump source (electric power supply for QDLs)
- Two reflectors (rear mirror and output coupler) to reflect the light in phase (determined by the length of the cavity) so that the light will be further amplified by the active medium in each round-trip (multipass amplification). The output is partially transmitted through a partially transmissive output coupler where the output exits as a laser beam ( $R = 80\%$  in the figure)

The active layer (QD or QW) is embedded in an optical waveguide (material with refractive index smaller than that of the active layer). Wavelength of the emitted light is determined by the energy levels of the QD rather than the band-gap energy of the dot material. Therefore, the emission wavelength can be tuned by changing the average size of the dots. Because the band-gap of the QD material is lower than the band gap of the surrounding medium we ensure carrier confinement. A structure like this, where carrier confinement is realized separately from the confinement of the optical wave, is called a separate-confinement heterostructure (SCH).

Figure 6 An ideal QD laser consists of a 3D-array of dots with equal size and shape, surrounded by a higher band-gap material (confines the injected carriers). The barrier material forms an optical waveguide with lower and upper cladding layers (n-doped and p-doped AlGaAs in this case).