

## UNIT IV : Semiconductor Physics

- To know properties of different materials (which we need to use for different applications) we must know behaviour of atoms in that material. & behaviour of atoms depends on behaviour of electrons in those atoms.  
Hence to explain behaviour of electrons different theories were put forth.

### Free Electron Theory of metals :-

- First proposed by Drude & later improved by Lorentz & hence theory is called Prude-Lorentz theory.

#### Basic assumptions made in the theory:

- All metals contain a fixed number of valence electrons forming an electron gas which are free to move throughout volume of metal like molecules of a gas.
- Electron velocities in metals obey classical Maxwell-Boltzmann distribution of velocities.
- The repulsive force between negatively charged electron is ignored & electric field due to +ve ions is assumed to be uniform.
- Electrons move from one point to another randomly with velocities depending on temperature. At R.T. velocity is about  $4 \times 10^5$  m/s.
- Kinetic energy of  $e^-$  is given by  $\frac{3}{2} kT$ , k: Boltzmann const  
T - absolute temp.
- In absence of external electric field,  $e^-$  move in random directions
- When electric field is applied, free  $e^-$  move towards +ve terminal of battery supply. Hence  $e^-$  will experience two motions due to temp & drift motion
- While drifting toward positive of supply,  $e^-$  collide with positive ions. During each collision there is loss of drift vel  
Average distance covered by an  $e^-$  b/w collisions is called

'mean free path'  $\lambda$  & time taken to cover this distance is relaxation time  $\tau$ .

As the temperature increases, vibration of ion cores increase hence resistivity increases with increase in temp in metals.

\* Classical free electron theory failed to explain

- specific heat capacity value based on classical theory shows it is independent of temp. but from quantum theory it is found it directly depends on temp.

- classical theory failed to explain occurrence of long mean paths c  $10^8$  or  $10^9$  times

- classification of solids on band theory i.e. metals, semiconductors & insulators can not be done by classical theory

- Positive values of Hall coefficient of metals could not be explained by classical theory

- classical theory also failed to explain photoelectric effect, compton effect & black body radiation.

\* Quantum Free electron Theory:

- Quantum mechanical behaviour of electron gas was 1st investigated by Sommerfeld.

Quantum theory was developed on the basis of Fermi-Pirac statistics & successful in explaining behaviour of electron cloud.

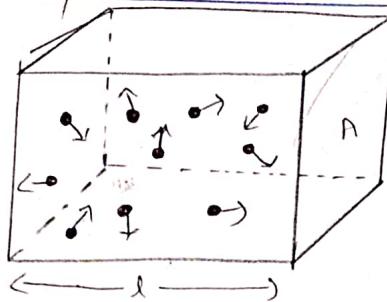
In Sommerfeld's model, it is assumed that free electrons are valence electrons of atoms of metals. These electrons are free to move within the metal but can not come out of metal surface due to presence of high potential barrier at the surface. Potential inside the metal (conductor) is zero, Thus, metal act as a potential well for free electrons.

\* Band theory:

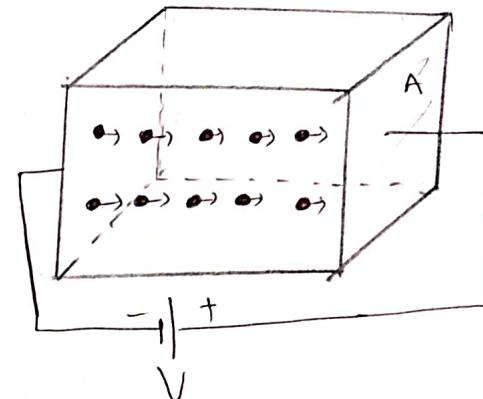
Band theory explained nature of potential as a periodic potential & explained different bands in solids.

## \* Electrical conductivity of conductors & semiconductors:

### ① Conductivity of Conductors :-



(a) Random motion



(b) Directed motion.

- Inside material, the free electrons move freely along all directions. These free electrons are called conduction electrons & they form free electron cloud / free electron gas / Fermi gas.
- In absence of an external electric field, electrons move randomly in all directions. When we apply an electric field, random motion becomes directed. This type of directed motion is called 'drift' & the velocity 'v' with which they are moving is 'drift velocity'. Drift velocity depends on electron mobility ' $\mu_e$ ' & applied electric field E.  
 $\therefore$  Drift velocity is given as:

$$V = \mu_e E \quad \text{--- I}$$

$\mu_e \rightarrow$  mobility  $\Rightarrow$  How fast electron can move through material which is under influence of external electric field.

Let,  $A$  = Conductor cross-section area

$n$  = electron density (no. of free electrons per unit volume)

$l$  = length of conductor

$V$  = Voltage applied across two ends of conductor.

$E$  = Applied electric field.

- Charge crossing the cross section ' $A$ ' of conductor in unit time is equal to  $n \times (v \times A) e$ . This rate of flow of charge constitutes the current.

$$I = n v A e \quad \text{--- II}$$

Substitute I in II eq<sup>n</sup>:

$$\underline{I = n \mu e E A e}$$

Also,  $E = V/l$ .  $\therefore I = n \mu e \frac{V}{l} A e$

Rearranging:  $\frac{V}{I} = \frac{l}{A} \cdot \frac{1}{n \mu e e}$

Ohm's law  $\rightarrow \frac{V}{I} = R \quad \therefore R = \frac{l}{A} \cdot \frac{1}{n \mu e e}$

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

Comparing R.H.S of both  $\Rightarrow$

$$\therefore \boxed{\rho = \frac{1}{n \mu e e}}$$

$\rho \rightarrow$  Resistivity of that conductor  
~~ohm.m~~

We know, conductivity ( $\sigma$ ) =  $\frac{1}{\rho}$ .  $\Rightarrow \boxed{\sigma = n \mu e e}$

$\sigma$  unit  $\rightarrow$  mho/m, also called Siemens/m.

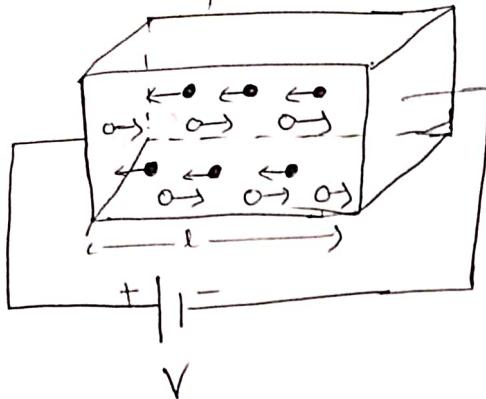
\* Current density (J)  $\rightarrow$  current flowing across unit cross section.

$$J = \frac{I}{A} = \underline{n \mu e E}$$

$$\Rightarrow \boxed{J = \sigma E} \quad \text{or} \quad \boxed{\sigma = \frac{J}{E}}$$

This is also called as 'microscopic form of Ohm's law'

## ② Conductivity in a Semiconductor :-



Current flowing in a semiconductor.

In semiconductors, the current will be due to motion of electrons as well as of holes.

$n_e \rightarrow$  electron density in conduction band

$n_p \rightarrow$  hole density in valence band

$\mu_e \rightarrow$  mobility of electrons ;  $\mu_p$  - mobility of hole

$v_e \rightarrow$  Drift velocity of  $e^-$ ,  $v_p \rightarrow$  drift velocity of hole

$A \rightarrow$  Cross section of semiconductor.

$V \rightarrow$  Applied voltage across length  $l$ .

$\therefore$  Current due to electrons :  $I_e = n_e v_e A e$ .

Current due to holes :  $I_p = n_p v_p A e$ .

$\therefore$  Total current flowing through semiconductor :

$$I = I_e + I_p = A e (n_e v_e + n_p v_p)$$

$$\text{Drift velocity} \Rightarrow v_e = \mu_e E = \mu_e \frac{V}{l} \quad \&$$

$$v_p = \mu_p E = \mu_p \frac{V}{l}$$

$$\therefore I = A e \frac{V}{l} (n_e \mu_e + n_p \mu_p)$$

$$\therefore \frac{V}{I} = \frac{l}{A} \frac{1}{e(n_e \mu_e + n_p \mu_p)} \Rightarrow R = \frac{l}{A} \frac{1}{e(n_e \mu_e + n_p \mu_p)}$$

$$\text{Also, } R = \rho \frac{l}{A} \Rightarrow \boxed{\rho = \frac{1}{e(n_e \mu_e + n_p \mu_p)}} \text{ ohm-m.}$$

$\therefore \rho \rightarrow$  resistivity.

$$\therefore \boxed{\rho = e(n_e \mu_e + n_p \mu_p)} \text{ mho/m.}$$

$$\text{Also, } J = \frac{I}{A} = e(n_e \mu_e + n_p \mu_p) E = \underline{\underline{\sigma E}}$$

### ① For Intrinsic semiconductors :-

$$n_e = n_p = n_i$$

$$\therefore \boxed{\sigma_{in} = e n_i (\mu_e + \mu_p)}$$

### ⑩ For N-type Semiconductor:

electron concentration is much greater than the hole concentration :  $n_e \gg n_p \Rightarrow n_{\text{elle}} \gg n_{\text{p,h}}$

$$\therefore \delta_N \approx e n_{\text{elle}}$$

Electron concentration is mostly because of donor impurity

$$\underline{n_d}$$

$$\therefore \boxed{\delta_N \approx e n_d n_{\text{elle}}} \quad n_d \rightarrow \text{concentration of } e^- \text{ from donor impurity}$$

### ⑪ For P-type semiconductor:

Electron concentration is negligibly small in comparison to hole concentration.  $n_p \gg n_e \Rightarrow n_{\text{p,h}} \gg n_{\text{elle}}$

$$\therefore \delta_p \approx e n_{\text{p,h}}$$

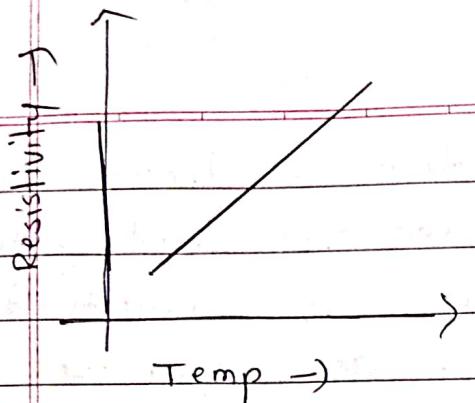
Acceptor atoms concentration  $n_a$ :

$$\therefore \boxed{\delta_p \approx e n_a n_{\text{p,h}}}$$

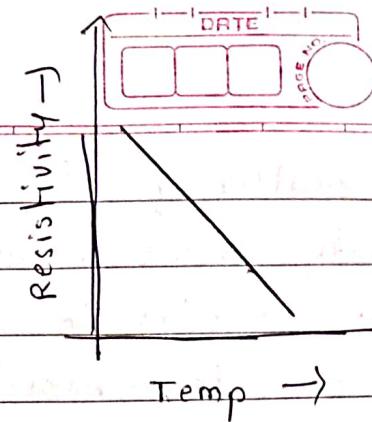
## + Influence of External factors on conductivity / Resistivity:

### ① Temperature:-

- In case of metals, the increase in temperature increases vibrations of lattice points. which causes more electron collisions because of which drift velocity of electron decreases.
- Hence in case of metals, conductivity decreases with rise in temperature & resistivity increases with increase in temperature.
- In case of semiconductors, there is small energy gap between conduction & valance band. As temperature increases, more number of electrons get excited from valance band to conduction band. which creates electron-hole pair & both will participate in conduction. As the conduction charge density increases with temp.
- Hence conductivity of semiconductor increases with increase in temperature & hence resistivity decreases with increase in temp.



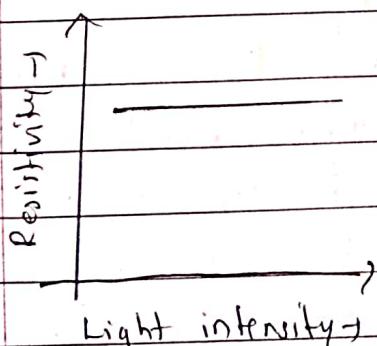
(a) metals



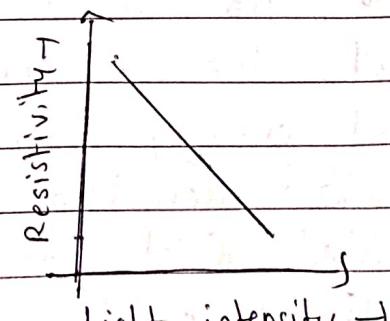
(b) semiconductors

## ② Light:

- In metals, when light is incident & energy of photon is more than a critical value electron is ejected from metal surface. But this doesn't affect the overall resistivity of metal. Hence resistivity do not depend on light.
- In semiconductors, when photon of energy equal to energy difference between valance & conduction band incident, photon will be absorbed & electron will be excited to the conduction band leaving a hole in valance band. Hence, resistivity decreases with increase in light intensity of light.



(a) metals



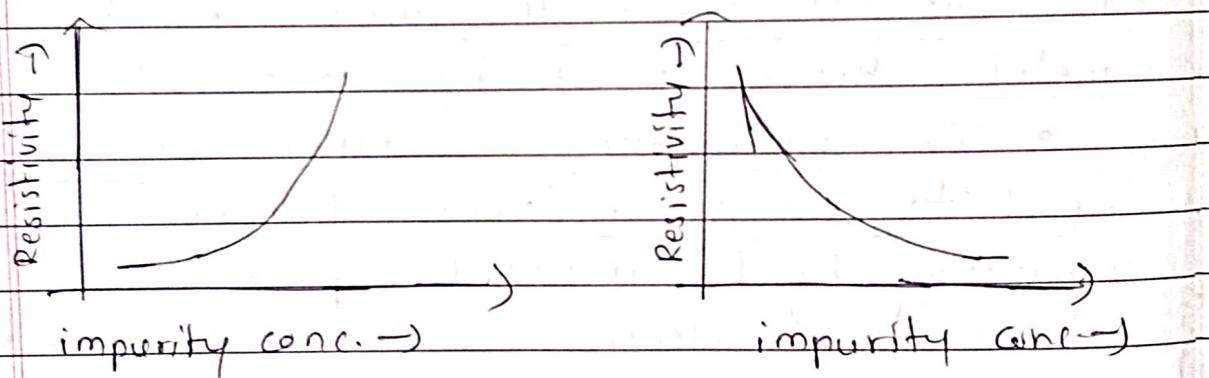
(b) Semiconductors

## ③ Impurity:

- In metals, presence of impurity increases

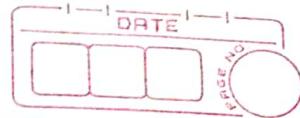
scattering of conduction electrons at impurity atoms, which decreases drift velocity, which results in decrease in conductivity or increase in resistivity as impurity concentration increases.

- In semiconductors, addition of proper impurity (doping) increases the charge carrier ( $e^-$  & holes) concentration which result in increase in conductivity or decrease in the resistivity.



#### \* Fermi energy:

- ① Fermi Level in conductors or metals:-
  - As solids are composed of large no. of atoms, energy levels form bands of energy. Filling of the bands follows rule such that states of lowest energy are filled first then next lowest & so on.. till all electrons are accommodated. The highest filled state is called 'Fermi level' & corresponding energy is 'Fermi Energy'  $E_F$ .
  - At ok, all states upto  $E_F$  are filled (full) & all states above  $E_F$  are empty.



- At higher temperatures, because of random thermal energy electrons will move from states below  $E_F$  to the states above  $E_F$ . But can not make transition from the state above  $E_F$  to the state below  $E_F$  as below  $E_F$  all states are filled.

- We can define it as:

Highest filled state in highest energy band which contains electrons in a metal at 0 K is called Fermi level & its corresponding energy is Fermi Energy  $E_F$ .

### (b) Fermi level in Semiconductors:

Reference level that gives probability of occupancy of states in cond<sup>n</sup> as well as valence band.

In case of intrinsic semiconductors, band of completely filled states called valence band is separated from band of unoccupied states called conduction band, by an energy gap  $E_g$ .

For intrinsic semiconductors, Fermi energy level lies exactly at the centre of energy gap  $E_g$ . (Forbidden gap)

$\Rightarrow$  states occupied in conduction band = states unoccupied in valence band.

For every electron in conduction band there is a hole in valence band.

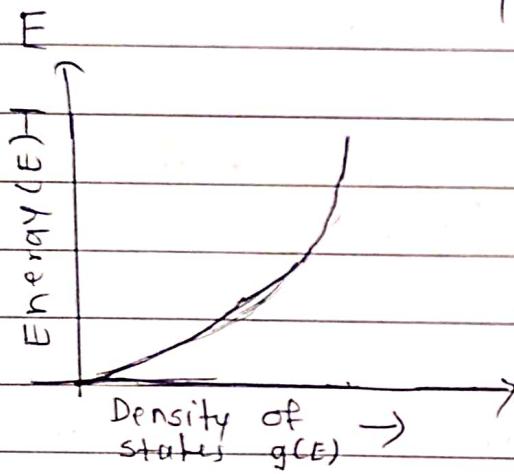
## \* Density State :

- Energy states available for accommodating the electrons.
- The number of states lying in the range of energies bet<sup>n</sup> E & E+dE is given by

$$g(E) dE = \frac{4\pi}{h^3} (2m)^{3/2} E^{1/2} dE$$

$g(E)$  → density of states function.

- The number of available states per unit volume per energy interval centred around  $E$



⇒ The number of available states decreases with energy & becomes zero at the edge of bottom of band

- The density of states gives number of available states but as the number of electrons is high, there will be some states which are occupied & some states unoccupied i.e. probabilistic case.

- There will be probability  $P(E)$  that it will occupy state of energy  $E$  or not so the number of carriers per unit volume within given energy range depends on both no. of available states & probability

$$\therefore N(E) dE = P(E) g(E) dE$$

$N(E)$  : carrier distribution function.

## \* Concept of Effective mass of electrons & holes:-

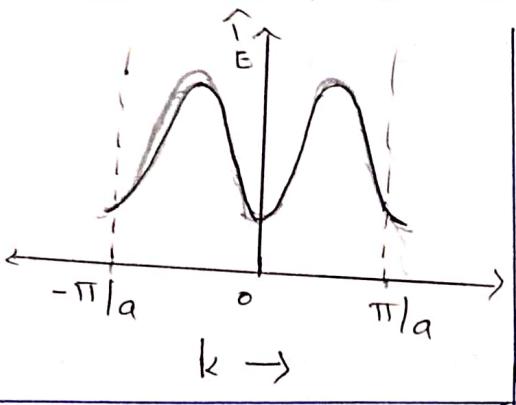
- An isolated electron or free electron moving in vacuum has a well defined mass & obeys Newtonian mechanics when accelerated by an electric field. But inside the crystal electron is not free to move.
- Consider one electron inside a material moving under external electric or magnetic field. The electron will experience periodic variation of potential due to ions while moving in the material.
- When electron is moving inside that periodic potential mass of electron is different than free electron in vacuum & referred as "Effective mass of electron"

$$m^* = \left( \frac{h}{2\pi} \right) \left( \frac{d^2 E}{dk^2} \right)^{-1} = h \left[ \left( \frac{d^2 E}{dk^2} \right) \right]$$

$h \rightarrow$  Planck's constant,  $k \rightarrow$  wave number  $= \frac{2\pi}{\lambda}$ .

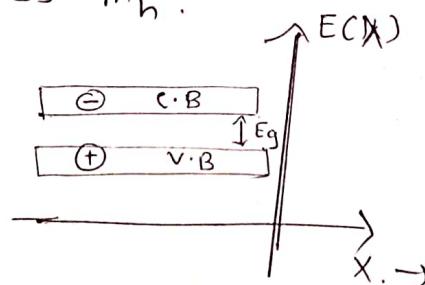
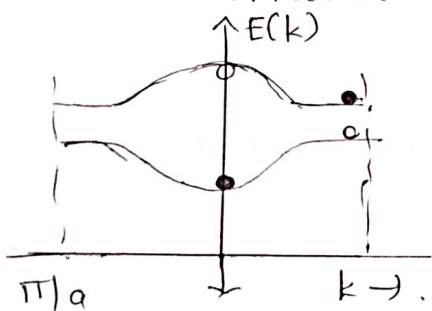
- \* Effective mass can be greater or even less than  $m$ . it can be negative also.

- When  $k=0$ , effective mass of electron approaches mass of free electron ( $m^* \approx m$ )
- As value of  $k$  increases, mass of electron approaches mass of free electron
- As value of  $k$  increases,  $m^*$  increases reaching a maximum value at a point of inflation. Above that point of inflation,  $m^*$  is negative &  $k \rightarrow \pi/a$ , it decreases to a small negative value,  $a \rightarrow$  lattice const.
- Effective mass of electron depends on its location  
Electrons near the bottom of the conduction band have an effective mass equal to mass of free electron while electrons near top of valence band have negative effective mass.



- Near the bottom of band, effective mass  $m^*$  has a constant value which is positive. As  $k$  increases,  $m^*$  varies as it is a function of  $k$ .
- Beyond inflection point,  $m^*$  becomes negative, region is close to top of the band.

- The velocity of electron decreases for  $k > k_0$ , thus acceleration is negative. Hence, velocity will be opposite to applied force, implying a negative mass.
- In this region of  $k$ -space, lattice exerts such a large retarding force on electron that it overcomes applied force & produces negative acceleration. Hence, in upper half of the band removal of an electron with negative effective mass is identical to creating in its place a particle of positive effective mass. This is called as hole & a hole is considered to have an effective mass  $m_h$ .



#### \* Fermi-Dirac Probability Distribution Function:-

- Electrons in solids obey Fermi-Dirac statistics. Result of statistical arrangement gives the distribution of electrons over a range of allowed energy levels at the thermal equilibrium:

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

$k \rightarrow$  Boltzmann's const.

$P(E)$ ; Fermi-Dirac distribution function  $\rightarrow$  gives the probability that an energy state of energy  $E$  will be occupied by an electron at absolute temperature  $T$ .

Quantity  $E_F \rightarrow$  Fermi energy.

i) For energy  $E = E_F \rightarrow$

$$P(E_F) = [1 + (e^{(0)})]^{-1} \Rightarrow P(E_F) = \frac{1}{2}$$

∴ Energy state at Fermi level has a probability  $\frac{1}{2}$  of being occupied by an electron for a temperature  $T = 0K$ .

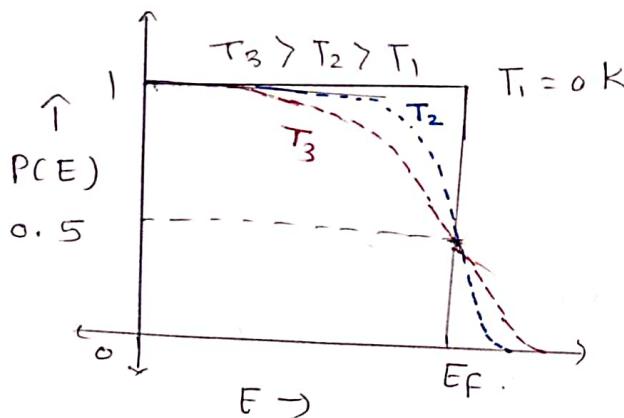
ii) At  $T = 0K$ , for  $E < E_F$ ,  $e^{(E-E_F)/kT} = 0 \therefore P(E) = 1$

Probability of finding an electron with energy less than Fermi energy = unity.

Or at  $T = 0K$ , all energy states below  $E_F$  are certainly occupied.

iii) At  $T = 0K$ ,  $E > E_F \rightarrow e^{(E-E_F)/kT} = \infty \therefore P(E) = 0$ .

∴ Energy states above  $E_F$  have zero probability of occupancy & they are thus empty.



\* Position of Fermi level in intrinsic Semiconductors:-

• Derivation of position of Fermi level in intrinsic semiconductors is based on following assumptions:

i) Width of conduction band & Valence band are small as compared to forbidden gap  $E_g$ .

ii) As band width is small, all levels in the band can be assumed to have same energy. The levels in conduction band have energy  $E_c$  while levels in valence band have energy  $E_v$ .

(11) At OK, solid is like an insulator  $\Rightarrow$  no conduction is possible  
 valence band - completely filled & cond<sup>n</sup> band completely empty

$\therefore$  F-D distribution func<sup>n</sup>  $\rightarrow$

$$P(E) = \frac{1}{1 + e^{(E-E_F)/kT}} \quad \text{--- I}$$

\* For, any other temp T,

$n_c$   $\rightarrow$  number of electrons in conduction band.

$n_v$   $\rightarrow$  number of electrons in valence band.

$N = n_c + n_v \Rightarrow$  no. of electrons in both bands.

$\therefore$  Probability to find an electron in cond<sup>n</sup> band:

$$P(E_c) = \frac{n_c}{N} \Rightarrow n_c = N \cdot P(E_c) \quad \text{--- II}$$

$P(E_c)$ : probability of an  $e^-$  having energy  $E_c$  in cond<sup>n</sup> band.

Also,  $P(E_c) = \frac{1}{1 + e^{(E_c-E_F)/kT}}$ . ( $\because$  for cond<sup>n</sup> band  $E = E_c$ )  $\quad \text{--- III}$

$\therefore$  Comparing eq<sup>n</sup> II & III

$$\therefore n_c = \frac{N}{1 + e^{(E_c-E_F)/kT}}$$

Also,  $n_v = \frac{N}{1 + e^{(E_v-E_F)/kT}}$ .

$$\therefore N = n_c + n_v = \frac{N}{1 + e^{(E_c-E_F)/kT}} + \frac{N}{1 + e^{(E_v-E_F)/kT}}.$$

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

$$\therefore (1 + e^{(E_c-E_F)/kT})(1 + e^{(E_v-E_F)/kT}) = 1 + e^{(E_v-E_F)/kT} + 1 + e^{(E_c-E_F)/kT}$$

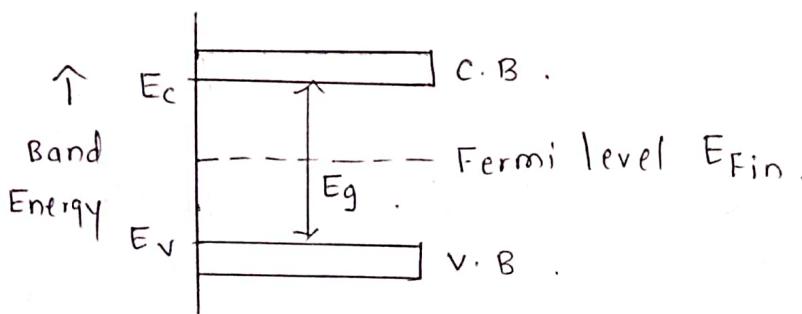
$$\Rightarrow \text{After rearrangement } \rightarrow e^{(E_c + E_v - 2E_F)/kT} = 1$$

$$\therefore \frac{E_c + E_v - 2E_F}{kT} = 0$$

$$\therefore E_c + E_v - 2E_F = 0 \Rightarrow$$

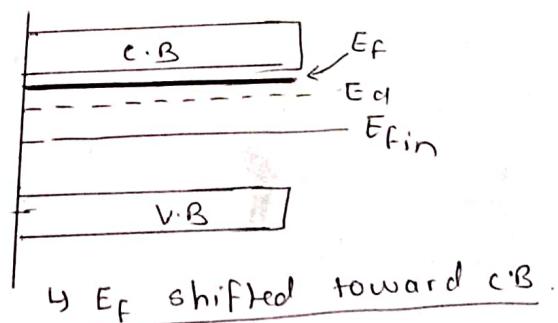
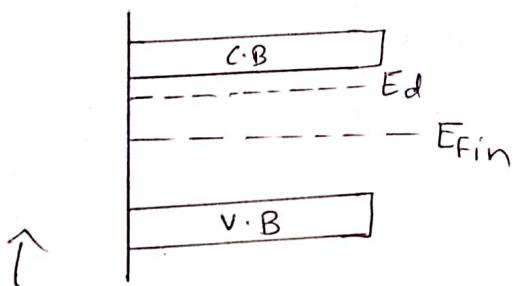
$$E_{F\text{in}} = \frac{E_c + E_v}{2}$$

∴ Position of Fermi level in intrinsic semiconductor is exactly in the middle of forbidden gap.



\* Position of Fermi level in N-type Semiconductors :-

- o N-type or pentavalent impurity semiconductor has more cond'n electrons than holes. Because of which Fermi level get shifted above middle of forbidden gap.  
Donor energy levels are located very close to the bottom of unfilled conduction band. (For Ge  $\rightarrow 0.01\text{eV}$  below the lower edge of C.B.). Hence very less energy is required to raise an electron from donor level to C.B. where it is free for conduction of electricity.



Donor level  $- E_d$ .

$E_{F\text{in}} \rightarrow$  Fermi level in intrinsic semiconductor.

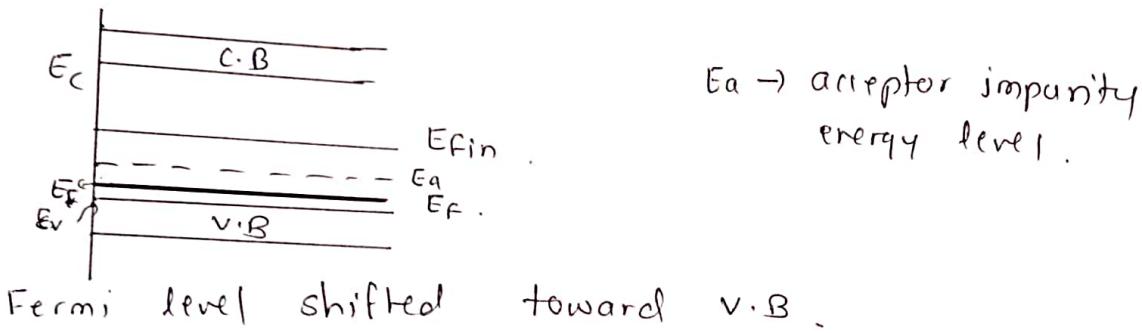
Also,  $E_F$  level & position depends on both doping & temp.

At, ok  $\rightarrow$  all donor levels are occupied & no electrons in C.B.  $\therefore P(E) = 1$  upto donor level,  $P(E) = 0$  at C.B.

$\therefore E_d \leq E_F \leq E_c$ .

## \* Position of Fermi Level in P-type Semiconductor :-

- Concentration of holes is greater than that of electrons.
- ∴ Fermi level get shifted below  $E_{fin}$  towards valance band top.
- Energy gap bet<sup>n</sup> acceptor level & v.B is very small hence less amount of energy required to move  $e^-$  from valance to acceptor level. hence more holes created at valance band.



$$\therefore E_v \leq E_F \leq E_a$$

## \* Dependence of Fermi level on Temperature & Doping Concentration:-

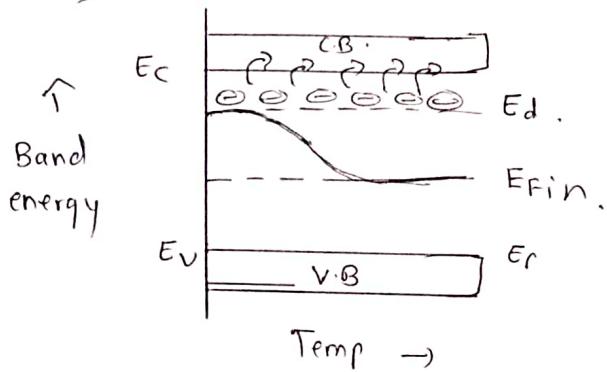
### ① Temperature :

#### 1-a : N type semiconductors :

- $E_F$  Fermi level is very close to bottom of C.B.
- At very low temperature, large number of atoms stay in unionised state for certain temp range called 'freeze out range'. very few  $e^-$  in C.B due to donor impurity.
- ∴ Fermi level lies above energy level of donor & bottom edge of C.B.

- With increase in temperature, large number of donor atoms ionise & donor level gradually decreases & Fermi level also decreases. At certain temperature Fermi level coincides with donor energy level. As temperature is increased further,  $e^-$  density in C.B. will reach maximum. Which is known as 'saturation Range'

- A further increase in temperature results in generation of electron-hole pair due to bond breaking of covalent bond of intrinsic semiconductor atoms.
- As temp increases, contribution of  $e^-$  due to  $e^-$ -hole pair creation will become very high hence Fermi level approaches to intrinsic value i.e. at centre of CB & VB.
- At still higher temp, extrinsic semiconductor transforms to intrinsic semiconductor with Fermi level at the centre.

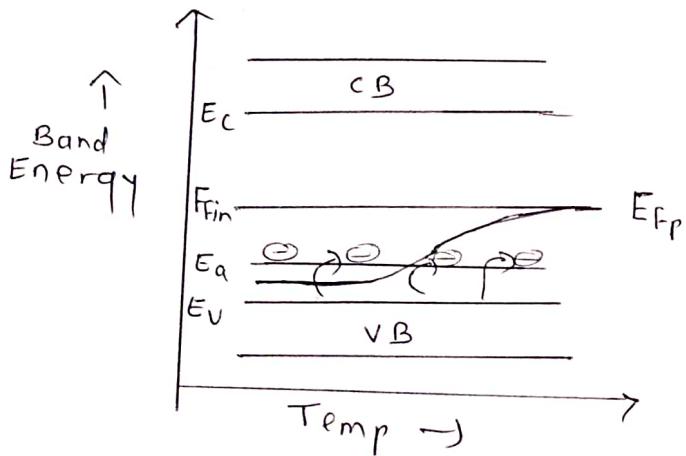


### I-b : P-type Semiconductor:-

- Acceptor energy level is close to top of valance band & Fermi level is below energy level of acceptor atoms & close to top of valance band.
- At very low temp, all acceptor levels are empty & only few electrons from valance band are excited to acceptor level. Fermi level is just above top of VB & just below acceptor level.
- With increase in temp. first intrinsic semiconductor atoms start ionizing.  $e^-$  from valance band will jump to acceptor level leaving holes in VB. ∴ Fermi level starts rising with ↑ in temp. Fermi level will shift from top of VB (below acceptor level) to above acceptor level.  
At particular temp all acceptor levels are full & hole density reaches maximum.
- A further increase in temperature, valance  $e^-$  will gain

enough energy to migrate to C.B. which will break  $e^-$ -hole pair. At high temp., contribution to charge carrier by intrinsic process becomes significant & Fermi level reaches to intrinsic value  $E_F = E_g/2$ .

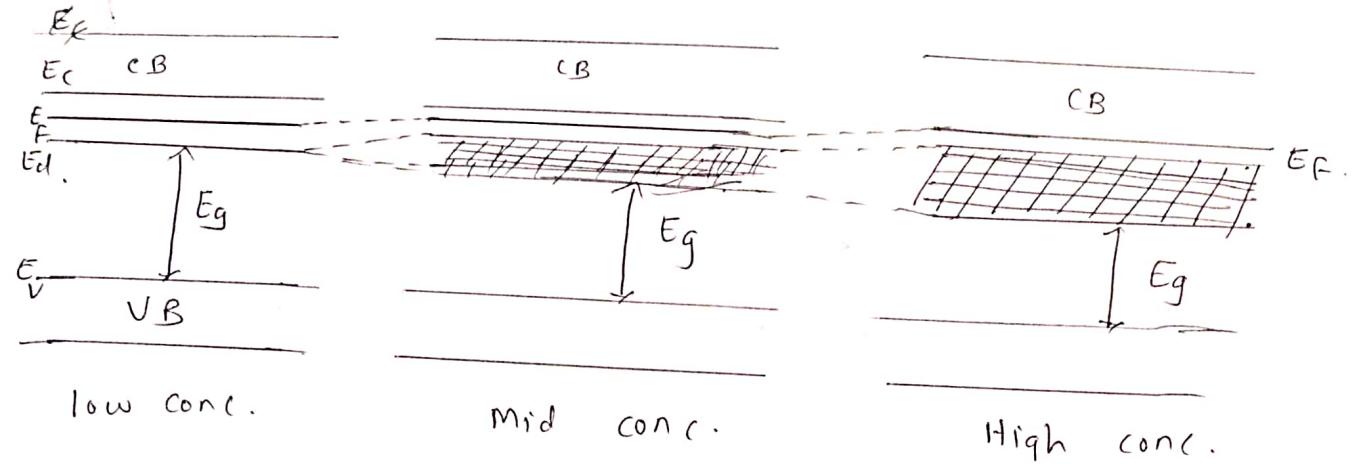
In extrinsic semiconductor get transformed to intrinsic semiconductor.



## ② Doping concentration :-

- The impurity atom energy levels are selected in such a way that energy level of impurity atom is very close to cond<sup>n</sup> band (in n-type for donor atom) or valance band (in p-type for acceptor atom)
- When donor atoms are added to intrinsic semiconductor, they form discrete energy level just below bottom edge of C.B. At low impurity concentration, impurity atoms are placed apart & they do not interact with each other. Hence they show discrete energy levels.
- With increase in concentration distance bet<sup>n</sup> them decreases & interaction bet<sup>n</sup> them increases. Which result in formation of energy band, below the C.B.
- With further increase in concentration, energy band of donor atoms will broaden & will overlap with C.B. ∴ Donor atoms will start to occupy upper val<sup>n</sup> vacant levels in C.B. Broadening of donor band also decreases forbidden gap & Fermi level get shifted upward closer to C.B. & with increase

The two impurity levels in impurity conc., it will finally move into the C.B. as donor band overlaps the C.B.



\* similarly, in P-type semiconductor, acceptor levels split & form a band with increasing impurity conc which overlap with valence band at high conc. Fermi level moves close to V.B & finally into V.B.

#### \* Diffusion & Drift current :-

Flow of current through semiconductor material is one of following types:

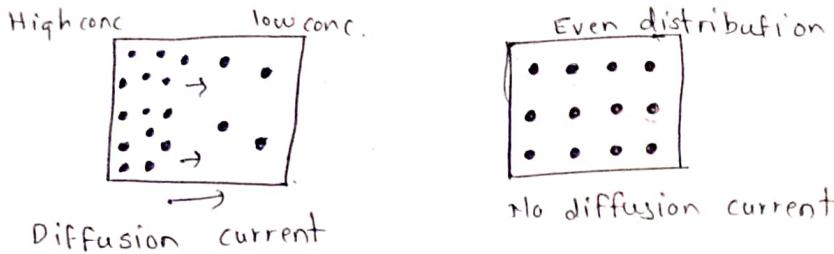
- ① Drift current due to motion of charged carrier in presence of an electric field.
- ② Diffusion current due to redistribution or spreading of charge carriers from area of higher conc to lower conc.

#### ① Drift current :

- when e<sup>-</sup> is subjected to an electric field in free space it will be accelerated in a straight line from -ve to +ve terminal of applied voltage.
- e<sup>-</sup> moving from -ve to +ve terminal of battery, they will collide with other e<sup>-</sup> or atoms & they are again directed to direction from -ve to +ve of applied voltage. this current  $\rightarrow$  drift current.

## ⑪ Diffusion current :

- In absence of electric field, there is uneven distribution of charge carriers (either holes or  $e^-$ )  $\Rightarrow$  number of  $e^-$  or holes is greater in one region as compared to other region. called as 'carrier concentration gradient'.

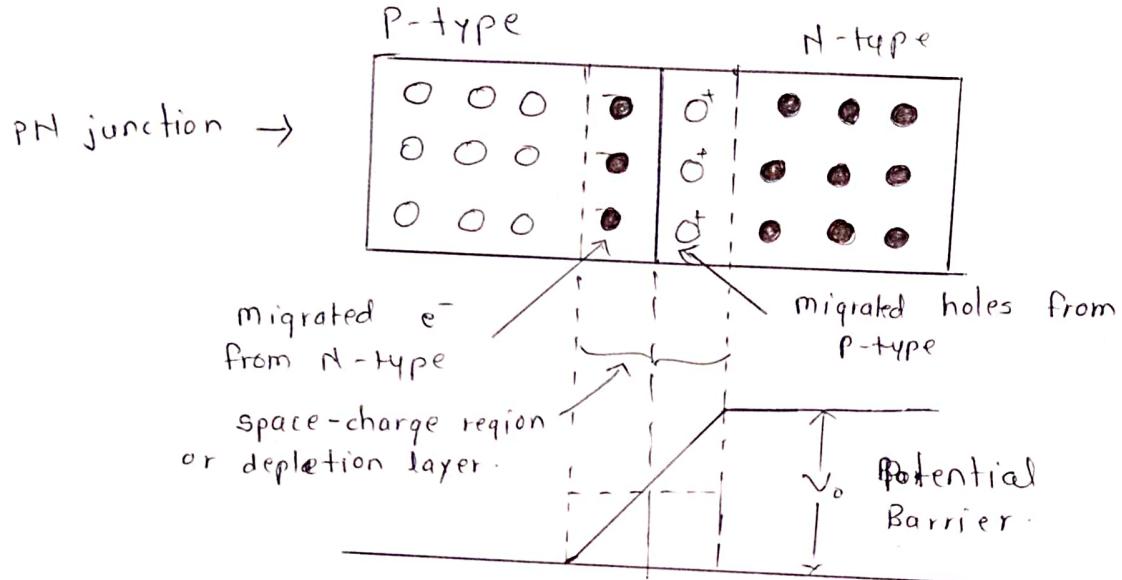


- As a result of uneven distribution of charge carriers, they tend to move gradually from region of high concentration to the region of low concentration. The process is called diffusion.
- This directional motion of charge carrier produces a current known as diffusion current. Process continues until charge carriers are evenly distributed.

## \* P-N Junction Diode :-

- When the crystal of a pure semiconductor is doped so that one half of it is P-type & the other half is N-type then the border bet<sup>n</sup> them is 'P-N junction'
- The junction diode is a two terminal device having one P-N junction. Junction diode passes a large current in one direction & almost no current in other direction. Thus such a diode can be used as a rectifier.
- Fermi level in P-type material is located close to the top of valance band & in N-type material Fermi level lies close to the bottom of conduction band.
- P-type material has more holes than free electrons & the N-type material has more free electrons than holes.
- When junction is made between these materials, holes will tend to move from p-type material into N-type material & electrons would tend to move from N-type material into P-type material, due to difference in concentration of holes & electrons on either side of p-N junction. This process is called as 'diffusion'

- The two materials then equalise their Fermi levels. Diffused charge carriers combine at the junction to neutralize each other.
  - Due to this neutralisation, a neutral (charge free) region / space called 'depletion layer' of width of order of few microns, is formed near the junction.

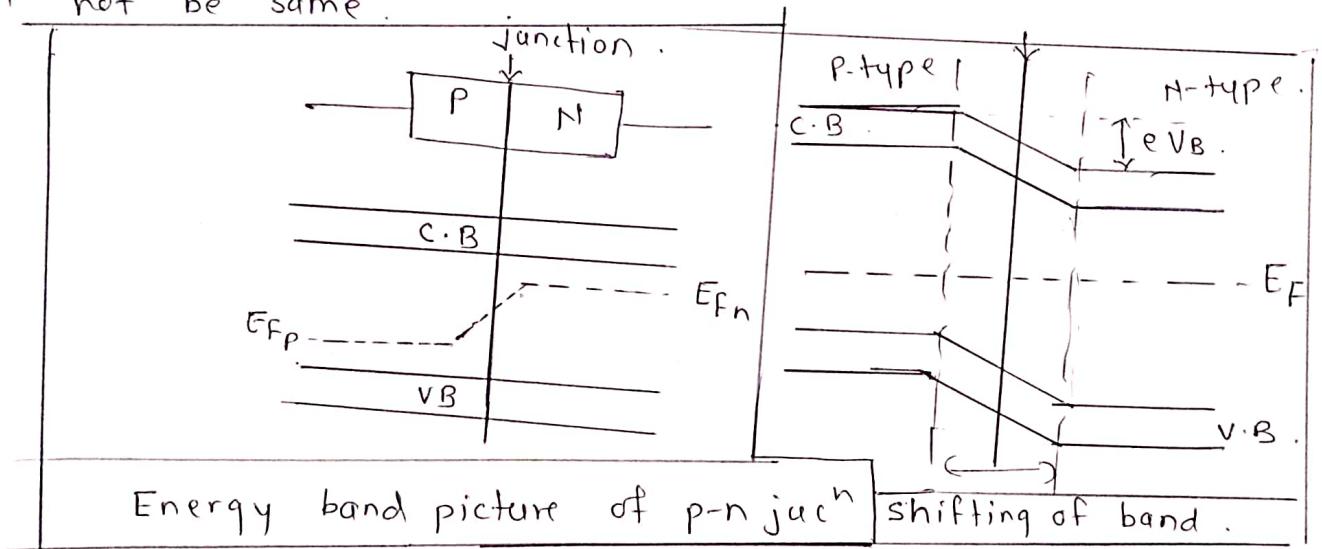


- Due to diffusion of holes from P to N region, negative ions are produced in P region.
  - similarly, due to diffusion of  $e^-$  from N into P region, positive ions are produced in N region. Both these +ve & -ve ions are immobile (stationary) & form parallel rows of opposite charges facing each other across the depletion layer. Because of this charge separation, electric potential  $V_0$  develops across junction under the equilibrium condition i.e. width  $juc^h$  externally isolated. Potential is called as 'junction potential' or 'barrier potential' & can be represented by 'space charge equivalent battery'.
  - Once potential barrier is established, further diffusion of majority charge carrier across  $juc^h$  is prevented.
  - On applying external voltage to P-N  $juc^h$ , diode cond<sup>n</sup> can occur only in one direction, so it is used as a rectifier.

\* Energy Band Picture of a p-N junction diode :-

## (g) Zero Bias:

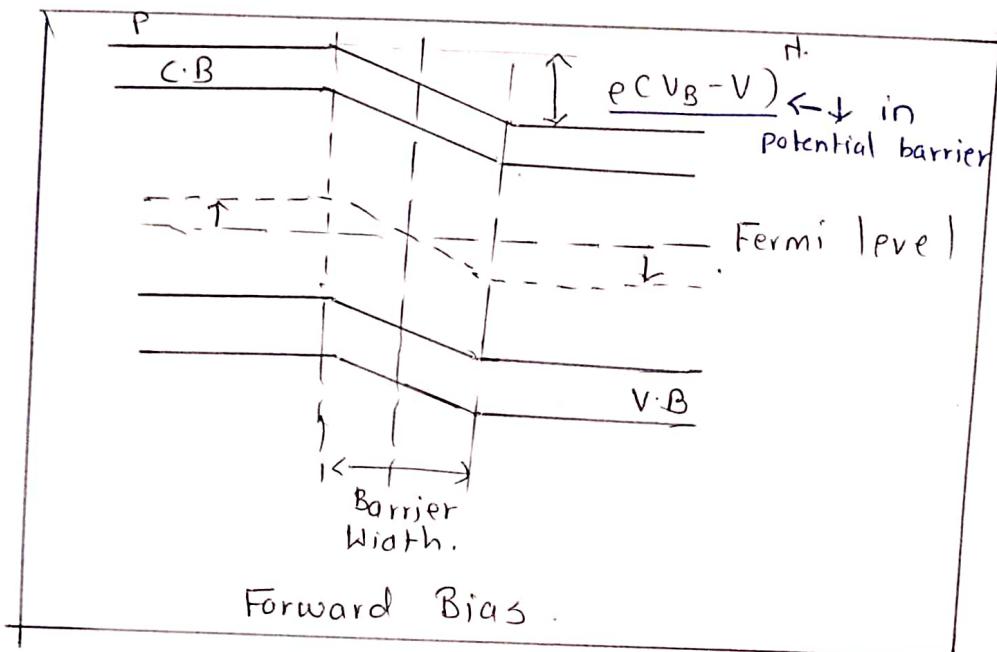
- Consider a P-N junction formed by fusing a P-type & an N-type semiconductor under unbiased condition (no external voltage applied)
- In this condition Fermi levels will have to realign such that it exists as a single energy level for entire specimen.
- Fermi level for P-type material is close to V.B & for N-type material it is close to ~~the~~ bottom of C.B.
- As Fermi level on P side is lower than Fermi level on N-side, electrons move across the boundary to the P-side & thereby equalize the Fermi levels.
- So the band edges in two specimen (P & N) shift themselves to make alignment of Fermi levels possible & band diagram will not be same.



- C.B. of P-type is shifted upward by  $eV_B$  over C.B. of N-type  $\Rightarrow V_B$  is 'Potential barrier' across the junction.
- Minority  $e^-$  in C.B. of P-type are at higher energy than majority  $e^-$  in C.B. of N-type.  
Hence when  $e^-$  will cross junction from P-region will not encounter the potential barrier while  $e^-$  crossing junction from N-region side will face barrier potential.

(b) Forward Bias :-

- P-side is connected to positive terminal & N-side to the negative terminal of the battery.
- Due to forward bias equilibrium conditions are disturbed & therefore energy levels / bands & Fermi levels are altered.



- As negative terminal is connected to N-type side, energy of  $e^-$  in N-region increases by amount  $eV$

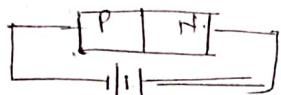
$V$ : externally applied potential (Voltage).

Result of which, Fermi level raises by  $eV$  & energy bands adjust their positions so as to suit the elevation of Fermi level.

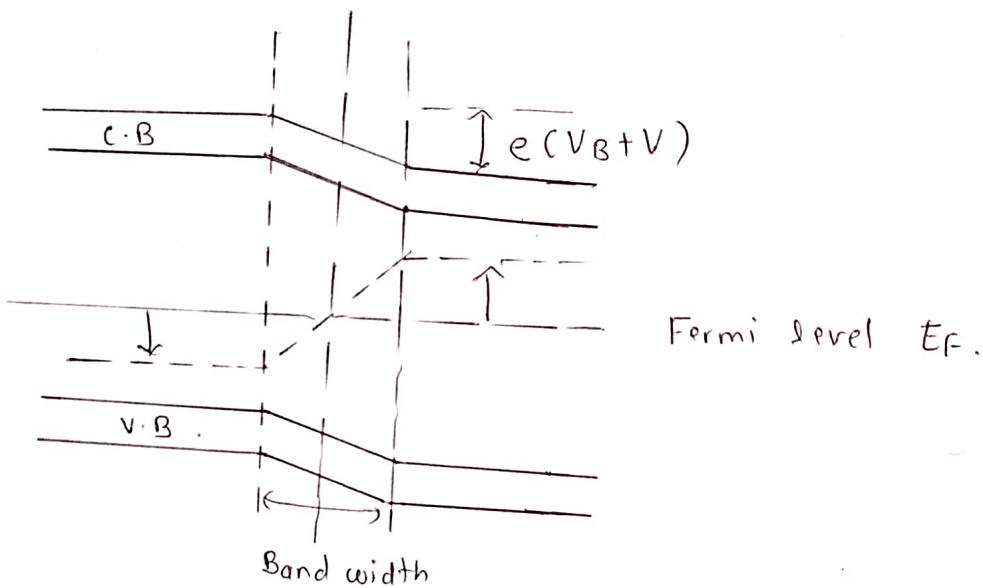
- Due to increase in energy in N-region side, potential barrier is reduced to  $e(V_B - V)$  & barrier width is also reduced
- Electrons crossing juc<sup>n</sup> from N-side will now face a low potential barrier & hence can easily cross the junction.
- For conduction to take place in a P-N diode, Forward bias potential should be greater than barrier potential.

### (C) Reverse Bias :-

- N-side is connected to the positive terminal & p-side to the negative terminal of the battery.
- Because of which Fermi level on N-side <sup>lowered</sup> by an amount  $eV$  raising barrier height to  $e(V_B + V)$  & hence width of depletion layer increases.



Reverse Bias.



- Electrons i.e. majority carriers in N-side will now face a greater potential barrier in crossing the junction.
- Hence, number of  $e^-$  crossing from N-side to P-side decreases & hence very much reduced.

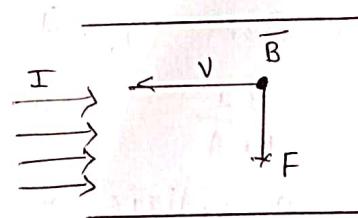
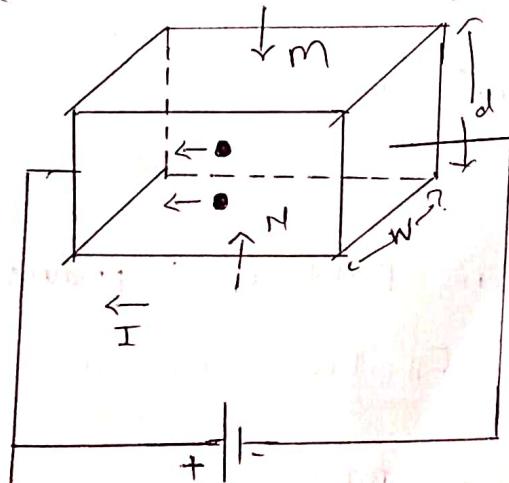
## \* Hall Effect & Hall coefficient :-

### o Hall Effect:

- To determine whether a material is N-type or a P-type semiconductor
- Conductivity measurement can not give information regarding what is nature of charge carrier (whether current is due to holes or electrons can not be determined)
- Hall effect is used to differentiate between two types of carriers. Also give information about density & mobility of charge carriers & also the sign of majority charge carrier.
- If a piece of conductor (metal or semiconductor) carrying a current is placed in a transverse magnetic field, electric field is produced inside the conductor in a direction which is normal to current & the magnetic field. This phenomenon is "Hall Effect" & voltage generated (due to that electric field) is called as "Hall Voltage"

## \* Explanation of the Effect :-

- Consider a material of n-type semiconductor. So current flow consists of almost entirely of electrons moving from (-ve to +ve terminal) right to left, direction of conventional curr. is from left to right.



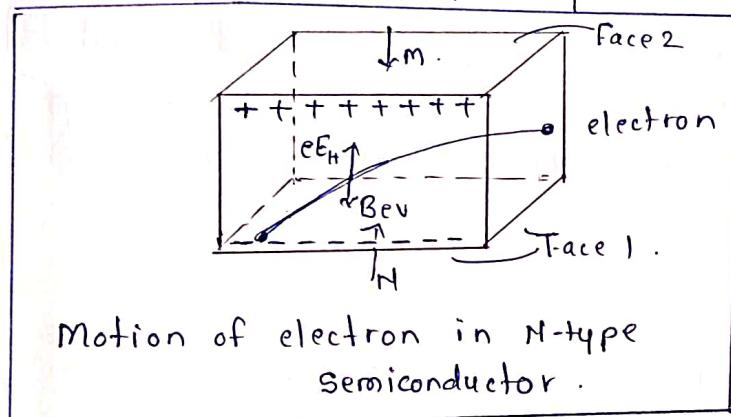
v - is drift velocity of electron moving perpendicular to the magnetic field  $B$ .  
Because of which, downward force  $F = Bev$  acts on electron. which causes electrons to be deflected in the downward direction.

Because of this deflection in motion, electrons will get accumulated at bottom surface of slab, (negative charge accumulated at bottom surface), leaving positive ions on top surface.

This gives rise to a potential difference along top & bottom faces of specimen across points M & N with bottom face being negative.

This potential difference, gives electric field  $E_H$  in negative Y-direction & this electric field exerts a force of  $e \cdot E_H$  on electrons in upward direction.

Under Equilibrium, upward force due to electric field just balances downward force due to magnetic field.



- Under equilibrium:

$$eE_H = eBv$$

$$E_H = vB - I$$

- If  $I$  is current in x-direction then,

$$I = nvAe$$

$$\Rightarrow v = \frac{I}{nAe} \quad \text{--- II}$$

$n$ : concentration of charge carrier.

Replace  $v$  from eq<sup>n</sup> II in eq<sup>n</sup> I

$$\therefore E_H = \frac{BI}{neA} \quad \text{--- III}$$

Also, Due to hall voltage  $V_H$ , electric field  $E_H$  is produced

$$\therefore E_H = \frac{V_H}{d} \quad \therefore \text{ substitute } E_H \text{ from eq<sup>n</sup> III}$$

$$\therefore V_H = \frac{1}{ne} \frac{BId}{A} \quad \Rightarrow V_H = R_H \frac{BId}{A}$$

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

Hall coefficient for any charge  $e$ .

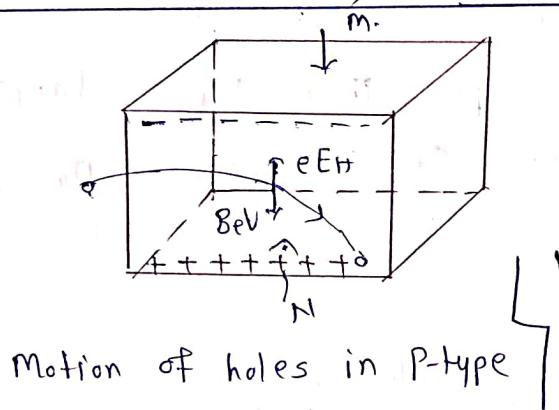
- In x-direction, if current density is  $J_x$ .

$$\therefore V_H = \frac{1}{n \cdot e} B J_x d \quad (\because I/A = J)$$

- For N-type semiconductor, majority charge carriers are electrons.

$$\therefore V_H = -\frac{1}{n e} B J d$$

- We can measure  $V_H$ ,  $B$  &  $J$  from which we can find  $R_H$  (Hall coefficient).



We can also derive the formulae for P-type material.

All formulae will be same except Hall eff coefficient will be positive

- Sign of the Hall voltage gives the sign of charge carrier & provides one of the few methods to find sign of charge carrier.

$$V_H = R_H \frac{B I d}{A} = R_H B J d$$

- Hall Coefficient ( $R_H$ )

- Hall coefficient  $R_H$  is determined by measuring the hall voltage that generate hall Field.

$V_H$  : Hall voltage across sample of thickness  $d$ .

$$\therefore V_H = E_H \cdot d$$

$$\text{Also, } V_H = R_H \frac{B I d}{A}$$

If  $w$  is width of sample,  $\therefore$  cross section will be  $A = dw$

$$\therefore V_H = R_H \frac{BId}{dw} = R_H \frac{BI}{w} \Rightarrow R_H = \frac{w}{BI} V_H = \frac{1}{nq}$$

$q$ : charge of carrier

- \* All quantities ( $w, B, I, V_H, q, R_H$ ) can be measured except for ' $n$ ', this relation is used to find the number of charge carriers per unit volume
- \* Hall coefficient varies inversely with  $n$  &  $q$ .
- \*  $R_H$  varies proportionately with width ( $w$ ),  $V_H$ .
- \* As  $R_H \propto 1/n$   $\therefore$  we can expect that  $V_H$  is larger for semiconductors than for metals ( $n_{\text{semicond}} < n_{\text{metals}}$ )

### \* Applications of Hall Effect :-

#### (i) To determine the type of semiconductor

- For N-type material hall coefficient is negative & for a P-type material it is positive.
- From sign of  $R_H$ , we can determine whether it is P-type or N-type material.

#### (ii) Calculation of charge carrier concentration:

- We can measure hall voltage  $V_H$  across top & bottom surfaces experimentally.
- If  $B$  is applied magnetic flux density, then

$$n = \frac{1}{e} \frac{BId}{A} \cdot \frac{1}{V_H}$$

- Using voltage & current measuring devices we can measure current  $I$  & voltage.
- From which we can easily find  $R_H$  & even  $n$  (no of charge carriers per unit volume)

### (III) Determination of mobility:

- If conduction is due to one type of charge carriers for example, electrons then

$$\sigma = n e \mu_e \Rightarrow \mu_e = \frac{\sigma}{n e}$$

We know,  $\frac{1}{ne} = R_H \therefore \underline{\mu_e = \sigma R_H}$ .

$$\boxed{\mu_e = \sigma \left( \frac{V_H A}{B I d} \right)}$$

- If we know  $\sigma$ , we can measure other parameters exptly we can find mobility of electrons  $\mu_e$ .

### \* Applications of pn junction diodes :-

#### ① Solar cells :

- Solar cell is a type of photo-voltaic cell.

Photoelectric cells are of three types:

① Photo-emissive cell    ② Photo-Voltaic cell & ③ Photo-conductive cell.

- All these cells are based on principle of photo-electric effect i.e. photon (light) energy converted into electrical energy.

- The photo-voltaic cells are based on photo-voltaic effect

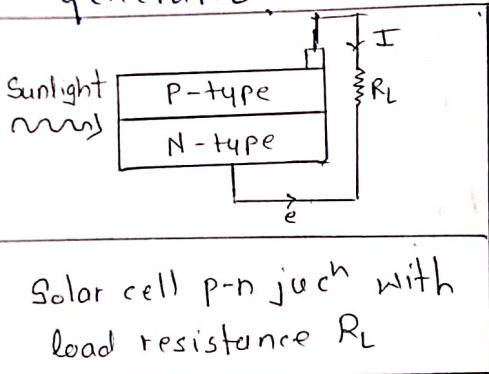
Photo-voltaic effect: Conversion of light into an electric current without aid of an external battery.

Voltage is developed in the cell. Solar cells are the best example of photo voltaic effect.

#### \* Action of Solar Cell :-

- If the photons with energy  $h\nu$  greater than the band gap  $E_g$  ( $E_c - E_v$ ), is incident on solar cell it will get absorbed.

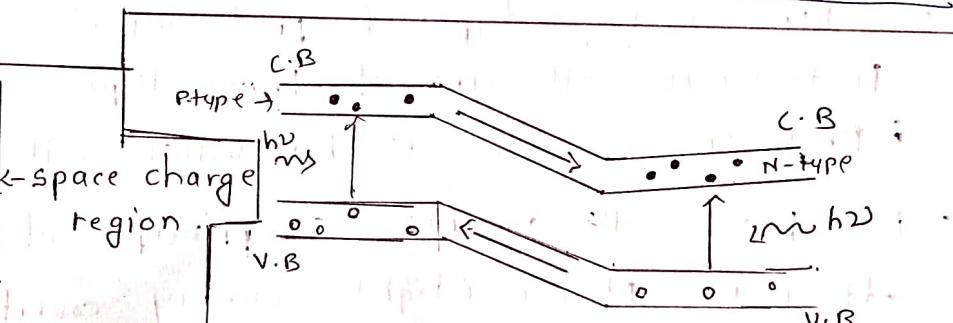
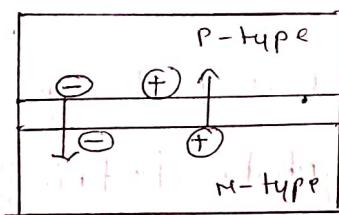
Electrons from valence band will move to conduction band. because of which electron-hole pairs will be generated. (holes in valence band, electrons in CB)



- Electrons & holes that are produced within a small distance of junction reach the space charge region by diffusion.
- Electron-hole pairs are separated by the strong barrier field existing across the N-side while holes in N-side move toward the P-side.

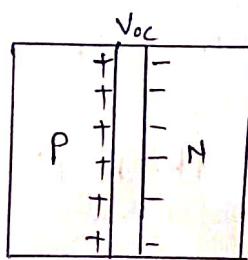
- When P-N junction is open circuited, the accumulation of electrons & holes on two sides of junc<sup>h</sup> gives rise to an 'open-circuited voltage'  $V_{oc}$ .

When a load resistance is connected across the diode, current flows in the circuit. This effect is "photo voltaic Effect".



- ① Diffusion of electrons & holes

- ② Energy band diagram corresponding to diffusion of  $e^-$  & holes



space-charge region

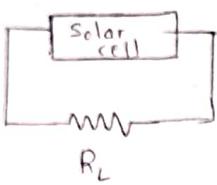
open circuited Voltage

- When diode terminals are short circuited, maximum current obtained is called 'circuit current'  $I_{sc}$ .

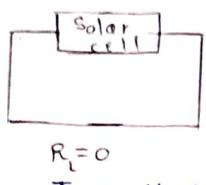
- When sunlight is incident on diode, current flows through it that current is proportional to the light intensity.

- The electrical energy generated in solar cell is in the form of dc voltage of approx 0.5 V.

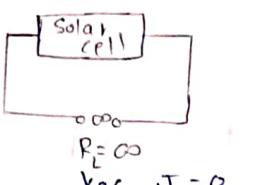
- Current varies with the surface area of photo-voltaic cell &



Solar cell  
with  $R_L$



$R_L = 0$   
 $I_{SC}, V=0$   
 $R_L$  minimum  
it will act  
as a short



$R_L = \infty$   
 $V_{OC}, I=0$   
 $R_L$  maximum  
it will open  
the circuit

- \* We know, power  $\rightarrow P = VI$
- \* If we want to find ~~for~~ maximum power, we need to take product of max voltage & corresponding current or maximum current & corresponding voltage
- But in solar cell, when Voltage is maximum corresponding current is zero & vice versa
- Hence we can not use  $V_{OC}$  or  $I_{SC}$  to measure maximum power.
- To get maximum power from solar cell, draw a line at  $45^\circ$  passing from origin, this line will cut the I-V curve at a point  $(V_m, I_m)$  where we will get maximum usable power.
- The ratio of maximum usable power to Ideal power is called as fill factor.

$$\therefore \text{Fill Factor } f = \frac{\text{Usable Power}}{\text{Ideal Power}}$$

$$f = \frac{V_m \cdot I_m}{V_{OC} \cdot I_{SC}}$$

↳  $V_m$  &  $I_m$  are maximum usable voltage & current obtained experimentally.

$I_{SC}$ : Short circuited current,  $V_{OC}$ : open circuit voltage.

$V_{OC} \cdot I_{SC}$ : Theoretically obtained maximum power of solar cell.

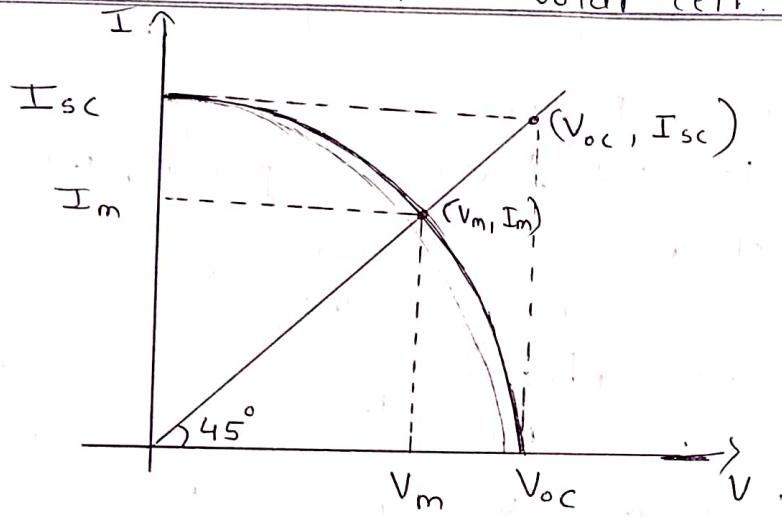
$V_m \cdot I_m$ : Experimentally obtained maximum power of the cell.

with intensity of incident light falling on it.

\* The efficiency( $\eta$ ) of solar cell is:

$$\eta = \frac{\text{Power output}}{\text{Incident solar Power}}$$

\* I-V Characteristics of a Solar cell:-



$I$  (current)  $\vee s$   $V$  (voltage)

\* IV characteristics of a solar cell.

- IV characteristics of solar cell is studied by changing load resistance  $R_L$  & measuring current flowing through & voltage across it.
- When load resistance  $R_L$  is zero, maximum current flows through it but voltage will be zero, this maximum current is called 'short-circuit current  $I_{sc}$ '.
- Current is max. (voltage is zero) hence it will be on current axis only.
- As  $R_L$  is increases, at particular point  $R_L$  becomes infinity hence current will be zero & voltage will reach a maximum value called "open circuit voltage"  $V_{oc}$  & as corresponding current is zero, it will lie on voltage axis only.

- As potential difference increases, recombination of electrons & holes also increases & hence we can not increase potential difference beyond certain limits.
- To reduce recombination, upper region is of smaller width so that carriers can reach junction before they recombine.
- When photovoltaic cells are connected in series or parallel, they form solar battery.

#### \* Advantages of Solar cells:-

- (i) It is environmentally clean source of energy.
- (ii) It is free & available in adequate quantities.
- (iii) Used in satellite communication.
- (iv) Used as power source in artificial satellites.
- (v) Can be used to supply power to places in remote areas & in fuel starved areas.

#### \* Disadvantages of Solar cells:

- (i) Even in hottest region on the earth, radiation flux rarely exceeds  $1 \text{ kW/m}^2$  which is the value of technological utilization. It requires large collecting areas in moving applications which result in excessive cost. hence its use is restricted because of high price.
- (ii) Solar energy varies with time because of day-night cycle.

#### \* Solar Cells Applications :-

- Solar cells are used extensively in satellites & space vehicles for long duration power supply.  
1st application was in 1958, to power 'Vanguard I' space satellite.

- Due to low weight, reliability & durability, they are imp source of power in space applications.

- Three broad categories :

### ① Industrial Applications :-

- Navigation aids : marine beacons, remote light beacons near airport & navigation lights around the world are now powered by solar cells which are reliable & cost effective.

- Alarm systems :

Railway signal, alarm system for fire, flood warnings, traffic lights, highway telephones are all being powered by solar cells.

- Defence Equipments :

many defence equipments like mobiles, telephones, remote radar, large instruments used in remote areas etc. now effectively powered by solar cells.

- Telecommunications :

Telecommunication equipments are often located in remote & inaccessible areas, for ex. islands, deserts etc. solar cells can be used in these cases.

- Emergency equipments :-

charging of batteries on rafts, boats & for providing essential services after natural disasters like earthquakes, floods etc. can be done essentially by solar cells.

- Automatic meteorological stations :

A meteorological station collects meteorological data at fixed time intervals at several locations & analyses them to predict weather forecasting accurately. Solar powered stations are reliable, economical & is relatively free of maintenance problems.

### II Social Applications:-

- In developing countries, to provide electric power to remote villages & islands solar cells are used.  
A small stand-alone type solar cell can provide a rural house enough power for lighting tubes, TVs & small refrigerator.
- Solar cell powered pumps are being installed to provide water & for irrigation purposes.
- Solar cell powered portable refrigerators are being used for transportation & storage of vaccines.
- Providing electricity to TV, for schools for educational & recreational purposes.

### III Consumer Applications:

- Large number of consumer items which are low powered are now being powered by solar cells. Some of these products are pocket calculators, clocks, torches, watches, radios, lights, electric fans, toys, battery chargers etc.