

## Band theory of solids

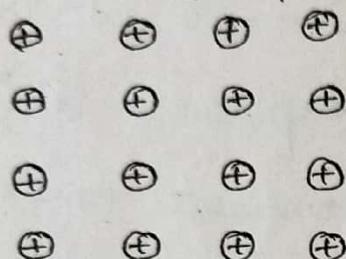
Bloch theorem: In Quantum free electron theory of metals, the conduction electrons are assumed to move freely inside a crystal of constant potential but will not come out of the metal because an infinite potential exists at the surface.

This theory successfully explained electrical conductivity, specific heat, thermionic emission etc. But it failed to explain why some solids behaves as conductors, some as insulators and some as Semiconductors etc. A solution to this problem is given by band theory of solids called zone theory.

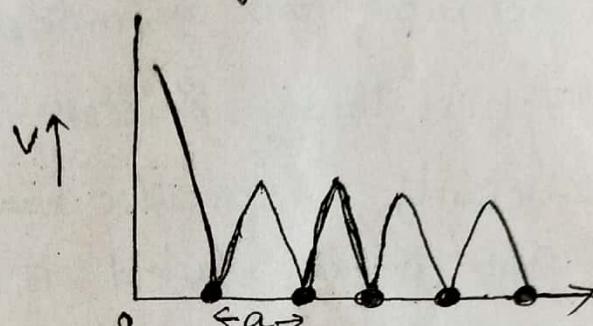
→ We know that Metals and alloys are crystalline in nature. A crystalline solid consists of a lattice which is composed of positive ion cores at regular intervals. i.e periodic positive ion cores. Inside the solid the free electrons are moving through these periodical positive ion cores and experiences varying potential or periodical potential.

The potential of the electron at the positive ion core is zero and is maximum at between the positive ions.

Consider the lattice in one dimension, i.e. an array of +ve ions along X-axis.



(a) Arrangement of +ve ions



(b) P.E Variation along x-direction

The above plot shows that the variation of P.E,  $V$  of a conduction electron as a function of its position  $x$ . It shows that the variation of potential energy along a straight line passing through the centres of the ion cores is periodic.

The potential energy periodicity is same as that of the lattice. Along x-direction in a crystal the potential function  $V(x)$  will be same at all points which are separated by a distance equal to 'a'. i.e  $V(x) = V(x+a)$

where  $x$  is the distance of  $e$  from the ion core.  
 $a$  is the periodicity of the lattice  
 Such a potential is said to be periodic potential.

The energies of electrons can be known by solving Schrodinger's wave equation in such a lattice.

The Schrodinger's wave equation for the motion of an electron along  $x$ -direction is given by

$$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2} [E - V(x)] \psi = 0$$

Bloch showed a type of solution for this equation

i.e.  $\psi(x) = u_k(x) e^{ikx}$ ,  $e^{ikx} \rightarrow$  a plane wave solution

where  $u_k(x)$  is a periodic function given by

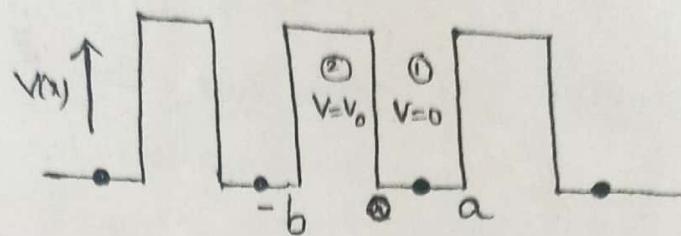
$$u_k(x) = u_k(x+a), \quad k = \frac{2\pi}{a}, \text{ wave vector}$$

### \* Behaviour of an electron in a periodic potential (Kronig-Penny Model)

It is not easy to solve the Schrodinger's equation with these potentials.

Kronig Penny treated that the P.E of an electron inside a crystal has the form of rectangular steps. i.e rectangular potential wells & potential barriers. This model is called Kronig-Penny Model.

The variation of potential energy of an electron while it is moving through the ion core is as shown



It consists of rectangular potential barriers and rectangular potential wells. Let  $a, b$  be the widths of potential well and potential barriers respectively.

Here we have two regions.

Region ①: In this region, between the limits  $0 < x < a$ , the P.E of the electron in the well is zero and hence the electron is assumed to be a free particle.

The one dimensional Schrodinger's wave equation for a free particle is

$$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2}(E-0)\psi = 0$$

i.e.  $\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2}E\psi = 0$ , Let  $\frac{2mE}{\hbar^2} = \alpha^2$

Then

$$\boxed{\frac{d^2\psi}{dx^2} + \alpha^2\psi = 0} \quad \text{--- ①}$$

Region ②: In this region, between the limits  $-b < x < 0$ , the P.E of electron in the potential barrier is  $V_0$  (say maximum)

The one dimensional Schrodinger's wave equation is  $\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2} [E - V_0] \psi = 0$

$$\therefore V_0 > E, \text{ then } \frac{d^2\psi}{dx^2} - \frac{2m}{\hbar^2} (V_0 - E) \psi = 0$$

Let  $\beta^2 = +\frac{2m}{\hbar^2} (V_0 - E)$ , Then the equation becomes 
$$\boxed{\frac{d^2\psi}{dx^2} - \beta^2 \psi = 0} \quad \rightarrow ②$$

If the electron moves under a periodic potential the solutions are obtained using the Bloch theory.

→ for both the regions the appropriate solution is of the form  $\psi(x) = u_k(x) e^{ikx} \rightarrow ③$

Differentiating equation ③ twice and substitute in ① & ② and then further solving it under boundary conditions.

Finally after applying the boundary conditions we will get four linear equations in A, B, C and D ( $A, B, C, D$  are constants). ~~the solutions~~

The solution for these equations can be obtained only when the determinant of the coefficients of A, B, C and D Vanish.

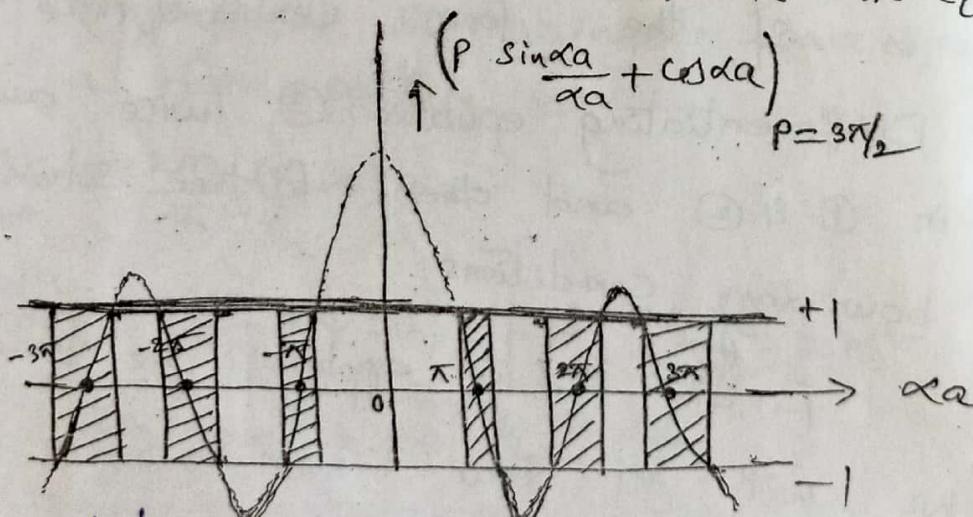
On solving the above determinant, we will get a condition that

$$P \sin \frac{\alpha a}{\lambda} + \cos \frac{\alpha a}{\lambda} = \cos ka$$

Where  $P = \frac{mE_0}{\hbar^2} ab$ , called Scattering power of

the potential barrier;  $\alpha^2 = \frac{2mE}{\hbar^2}$ , ie  $E = \frac{\alpha^2 \hbar^2}{2m}$

In this equation there are only two variables  $\alpha$  and  $k$ . We know that  $\cos ka$  can take the values from  $-1$  to  $+1$ . Therefore Left hand side of the equation must also fall in this range. A plot is made between the LHS equation and  $\alpha a$ .



Note:- The solution is defined only in the shaded region. ie only certain values are allowed. This implies that there are only certain allowed energy bands in crystal solids.

From the plot it is possible to determine the allowed values of  $\alpha a$ . To find the allowed parts of the curve, horizontal lines are drawn at  $\pm 1$  on vertical line as shown. From the graph it is observed that,

- \* → The conduction electrons in a periodical lattice ions possess the bands of allowed energy (shaded region) separated by forbidden regions (unshaded region)
- \* → As the value of ' $\alpha a$ ' increases, the width of the allowed energy bands increases and the width of the forbidden bands decreases.
- \* → When ' $P$ ' is increased, the B.E of the electrons with the lattice ions is also increased. Therefore the electrons will not be able to move freely and hence the width of the allowed energy band decreases. Especially for  $P \rightarrow \infty$  then the allowed energy bands becomes single energy levels. The energy levels in this case are discrete and similar to the energy levels of a particle (electron) in a constant potential box.

i.e., we have  $P \sin \frac{\alpha a}{\alpha a} = \cos \alpha a - \cos \alpha a$

When  $P \rightarrow \infty$ ,  $\sin \alpha a = \frac{(\cos \alpha a - \cos \alpha a)}{P} \times \alpha a = 0$

$$\Rightarrow \sin \alpha a = 0 \Rightarrow \alpha a = n\pi \Rightarrow \alpha = \frac{n\pi}{a} \Rightarrow \frac{P}{\alpha} = \frac{n\pi^2}{a^2} \Rightarrow \frac{2mE}{h^2} = \frac{n^2\pi^2}{a^2}$$

$$\Rightarrow [E = \frac{n^2\pi^2}{8ma^2}]$$

\*→ When 'P' is decreased the B.E of the electron decreases with the ions and thus moves freely through out the lattice ions.

When  $P \rightarrow 0$ , which leads to  $\alpha da = c \alpha k a$

$$\therefore \alpha a = k a \Rightarrow \alpha^n = k^n$$

$$\frac{2mE}{\hbar^2} = k^n$$

$$\therefore E = \frac{\hbar^n k^n}{2m} = \frac{\hbar^n}{4\pi^2} \times \frac{k^n}{2m}$$

$$= \left(\frac{2\pi}{\lambda}\right)^n \cdot \frac{\hbar^n}{4\pi^2} \times \frac{L}{2m}$$

$$E = \frac{P^n}{2m} \Rightarrow \boxed{E = \frac{1}{2}mv^2}$$

∴ This means that the electron is possessing K.E only and hence it is free to move and there is no forbidden band. Hence all the energy bands are allowed to the electron.

Thus by varying P from  $\infty$  to zero, the energies of the electron will vary from bound to continuous. ie the bound electrons become free electrons.

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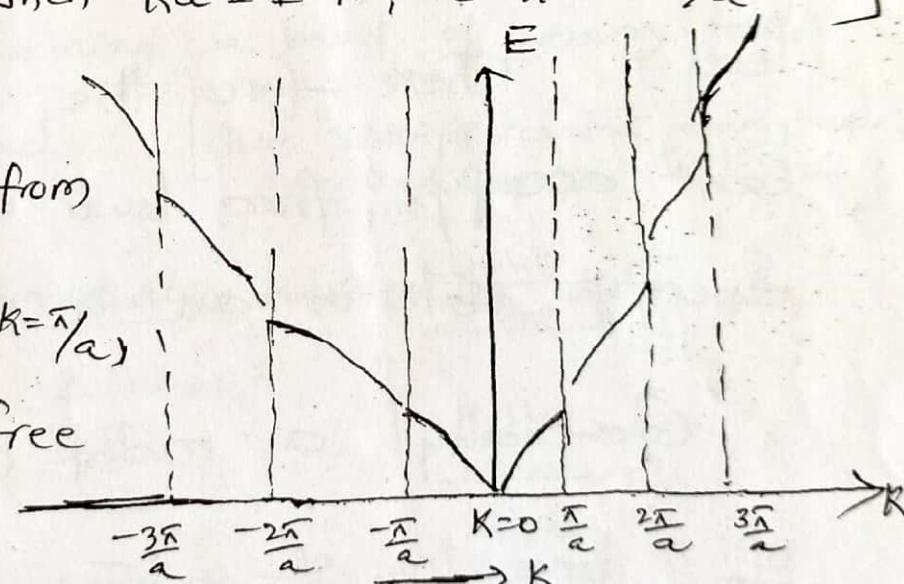
E-K curve: The free electrons moving in a periodic potential lattice can have energy values only in the allowed energy zones (or) regions.

The plot between the total energies of the free electrons Versus propagation Vector  $K$  is as shown. We observe that the curve is not continuous, it has discontinuities at

$$K = \pm \frac{n\pi}{a} \quad \left[ \because R \text{ is value of } ka \text{ lies between } -1 \text{ to } +1 \right]$$

When  $ka = \pm n\pi$ , i.e.  $K = \pm \frac{n\pi}{a}$

for  $n = 1, 2, 3, \dots$

In the figure from the region  $K = -\frac{\pi}{a}$  to  $K = \frac{\pi}{a}$ , the electron is free to move, the region  is known as allowed energy zone called first Brillouin zone. After a break in the energy value called forbidden band (or) region the electron have another allowed zone called Second Brillouin zone etc.

Conclusion: Therefore we can conclude that the electron can go from one Brillouin zone to the next Brillouin zone only if it is supplied with an energy equal to forbidden energy.

### Origin of Energy bands:

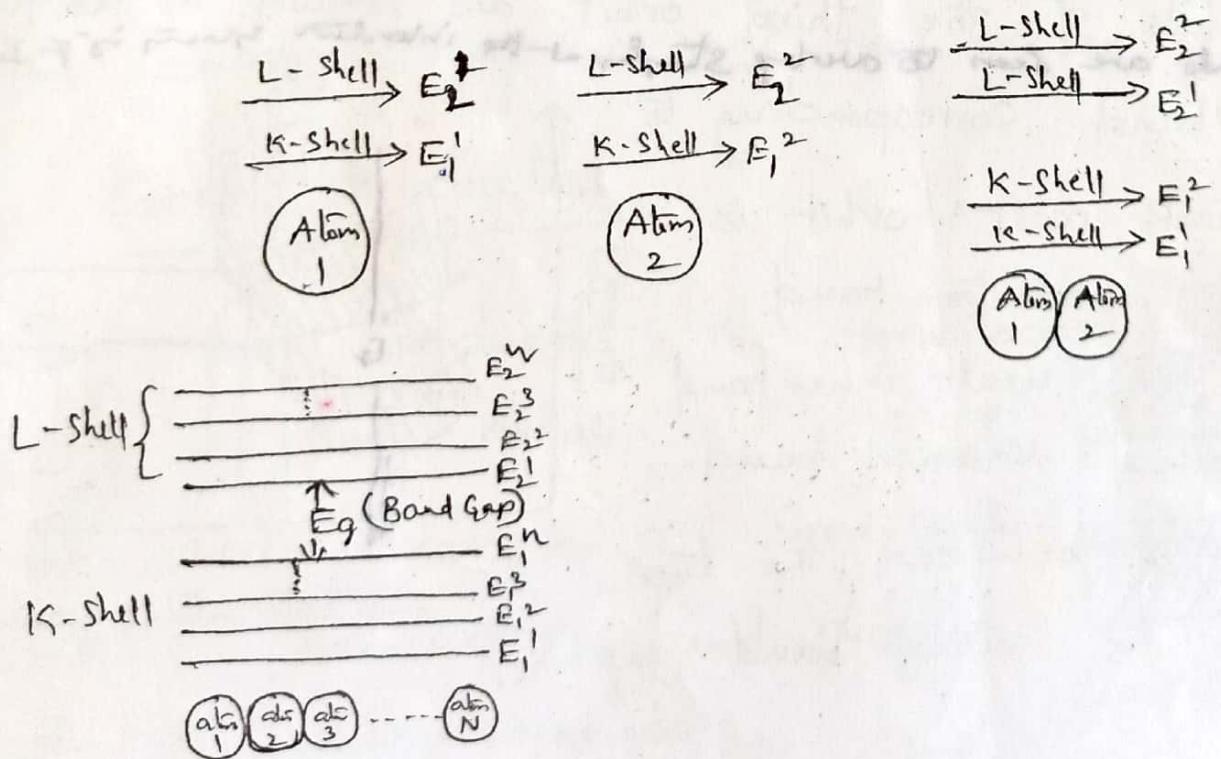
pauli's exclusion principle states that a maximum no. of two electrons (with opposite spin) can be accommodated in any energy level. Therefore the electrons in an atom can occupy from lower energy state to higher energy state in an increasing order.

Generally a metal (or) a solid consists of large no. of atoms. These atoms are very close to each other in a solid.

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At the interatomic distance decreases, the allowed energy levels of an electron of one atom overlap with those of neighbouring atoms. Hence in a solid the energy level corresponding to any one quantum no. splits up into many closely spaced levels, thus forming a band of energy called energy band.

Suppose when  $N$  no. of atoms are brought together to form a solid, the top most energy level for all  $N$ -atoms combines together and splits into  $N$ -closely spaced levels forming a band of energy levels called Valence band. [Here subscript represents energy levels & super script represents the atoms]



When an electric field is applied the electrons at the top of the Valence band receive energy and move to the next permitted energy band above the Valence band called conduction band (which contains un filled levels) and conduct electricity. There is a gap between the C.B and V.B called energy gap. It is denoted by Eg.

This is illustrated taking Sodium as an example in the figure.

When sodium atoms are brought together to form a Na-metal, the sharp energy levels of the Valence electron spread into bands. Only s and p orbitals of the third orbit are shown, in the figure. These bands are seen to overlap strongly at the interatomic spacing is  $\frac{1}{2}$  atom.

The band corresponding to

the outer most orbit is

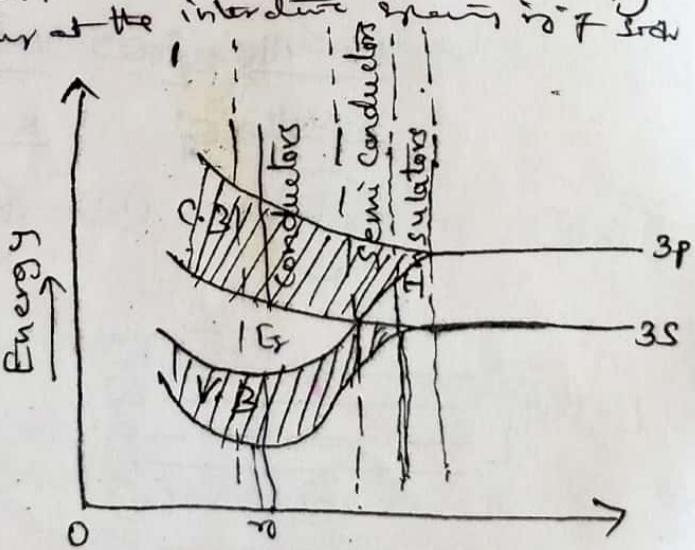
called conduction band

and the next inner band

is called Valence band.

The gap between the two

bands is called band gap.



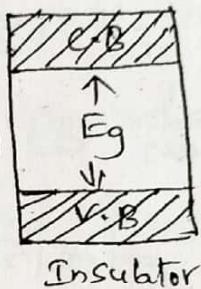
→ Inter atomic spacing

On the basis of band theory of solids, they can be classified into 3-categories.

1. Insulators
2. Semiconductors
3. Conductors

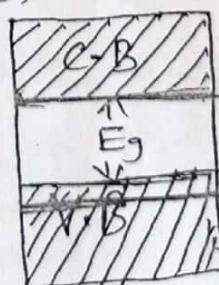
Insulators: In insulators, the energy gap is very high. Due to this, electrons can't jump from V.B to the C.B

In insulators, the valence electrons are tightly bound to their parent atoms. For example, in glass material the V.B is completely full at  $T=0K$  and the energy gap  $E_g$  is of the order of 10 eV. In Diamond the energy gap is of the order of 6 eV.



### Semi-conductors:

In semi-conductors, the forbidden gap is very small. Si, Ge are the best examples of semi-conductors. The energy band diagram of a semi-conductor is similar



Semi-conductors

to that of insulator. but the energy gap is relatively small and is of the order of 1 eV. The energy gap of Si is 1.1 eV and for Ge it is 0.72 eV.

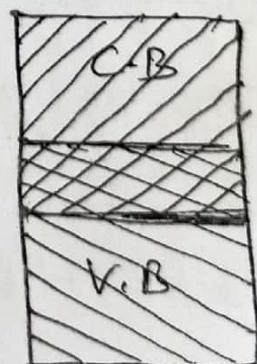
The electrical properties of these materials lies in between Insulators and Conductors.

When a small amount of energy is supplied the electrons can move from V.B to C.B easily.

### Conductors:

In case of conductors there is no forbidden energy gap. The Valence band and conduction band overlap each other. In C.B plenty of free electrons are available for the process of conduction. The electrons from V.B freely enters into C.B.

Ex: Cu, Ag, Al, Iron etc



Conductors

## Effective mass of an electron:

It is the mass of an electron when it is accelerated in a periodic potential and it is denoted by  $m^*$ .

Explanation: When an electron of mass  $(9.11 \times 10^{-31} \text{ kg})$  is placed in a periodic potential and if it is accelerated with the help of electric (or) magnetic field, then the mass of an electron will not constant and is varied. The Varying mass is called effective mass,  $m^*$ .

Consider an electron in the first Brillouin zone of state  $k$ ; when it is subjected to the electric field, the electron gains a group Velocity denoted by  $V_g$ .

$$\text{We have } V_g = \frac{1}{\hbar} \frac{dE}{dk}.$$

acceleration of the electron  $a = \frac{d^2r}{dt^2}$

$$\text{i.e } a = \frac{d}{dt} \left( \frac{1}{\hbar} \frac{dE}{dk} \right)$$

$$\text{i.e } a = \frac{1}{\hbar} \frac{d}{dt} \left( \frac{dE}{dk} \cdot \frac{dk}{dr} \right)$$

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

We have the momentum of the electron,

$$p = \hbar k \Rightarrow \frac{dp}{dt} = \hbar \frac{dk}{dt}$$

$$\text{but } \frac{dp}{dt} = F, \text{ then } F = \hbar \frac{dk}{dt} \Rightarrow \boxed{\frac{dk}{dt} = \frac{F}{\hbar}} \quad \text{--- (2)}$$

put (2) in (1), we get

$$a = \frac{1}{\hbar} \frac{d^2E}{dr^2} \times \frac{F}{\hbar} \quad \cancel{\times \frac{F}{\hbar}}$$

$$\Rightarrow \boxed{F = \frac{\hbar^2 a}{d^2E/dr^2}} \quad \text{--- (3)}$$

but from Newton's Second law, we have

$$F = m^* a \quad \text{--- (4)}$$

From (3) & (4), we get

$$\boxed{m^* = \frac{\hbar^2}{d^2E/dr^2}} \quad .$$

Special cases: ① if  $\frac{d^m E}{dk^2}$  is +ve, then  $m^*$  is +ve.

② if  $\frac{d^m E}{dk^2}$  is -ve, then  $m^*$  is -ve.

③ if  $\frac{d^m E}{dk^2}$  is zero, then  $m^*$  becomes  $\infty$ .

Consider the first Brillouin zone of state 'k'

In the E-K curve the first Brillouin zone can be divided into two bands.

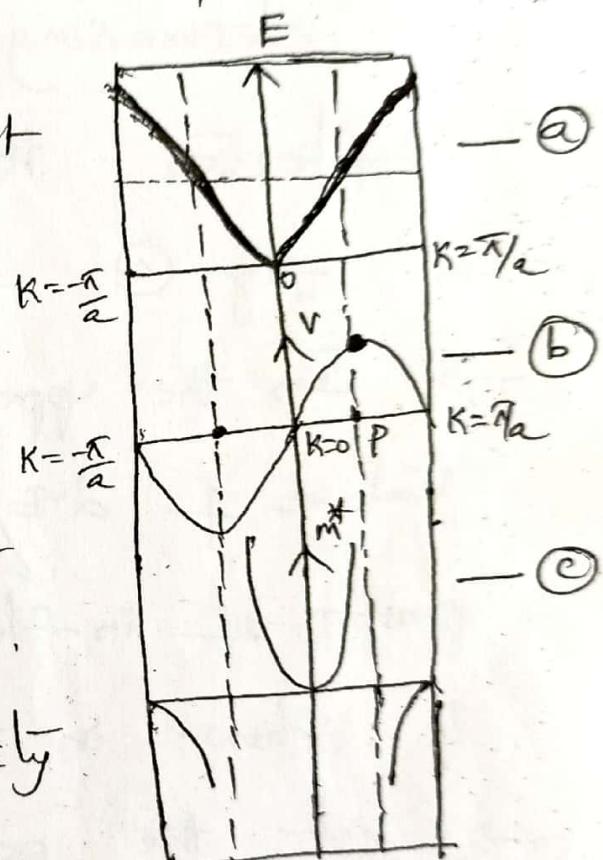
① upper band ② lower band

Fig ② represents the energy versus wave vector 'k' curve.

Fig ③ represents the Velocity versus 'k' curve.

At the bottom of the energy band, the velocity of the electron is zero and increases with the value of 'k' and becomes maximum (constant) at a point called point of inflection 'P'.

For further increase in the value of 'k', the velocity



decreases. The  $-ve$  values of the wave vector is also exhibits the similar behaviour.

→ From the curve ②, in the lower portion of  $E-K$  curve, the value of  $d^2E/dk^2$  is a decreasing function from the point of inflection, then  $m^*$  is  $+ve$ , and is shown in fig ③.

→ In the upper portion of  $E-K$  curve, the value of  $d^2E/dk^2$  is increasing from the point of inflection, hence  $m^*$  is  $-ve$  and is shown in the fig ④

→ At the point of inflection 'P', the value of  $d^2E/dk^2$  is zero, hence  $m^*$  is infinite.

Note: (i) As Velocity increases and becomes maximum then  $a$  is zero, hence  $m^* = \infty$  ( $\because m^* = \frac{F}{a}$ )

(ii) Above the point of inflection,  $v$  decreases which gives  $-ve$  acceleration hence  $m^*$  is  $-ve$ .  
 $\therefore m^* = F/v$

## Drift and Diffusion currents:-

Let us consider a semiconductor of length  $l$ . When an external electric field is applied to it, then the electric field exerts a force  $Ee$  on each carrier, so that the charged carriers accelerate with  $\frac{Ee}{m}$ . The velocities of electrons and holes increases in the opposite direction upto a certain constant value called drift velocity of carriers. The drift velocity of electrons and holes produce drift current in the material.

The current drift current density of electrons is  $(J_n)_{\text{drift}} = neV_{de} \quad \text{--- (1)}$

but from Microscopic form of Ohm's law, the current density of electrons can also be represented by,  $(J_n)_{\text{drift}} = \sigma_n E \quad \text{--- (2)}$

From (1) & (2)  $\sigma_n E = neV_{de}$

but from the definition of mobility of electrons,  $V_{de} = \mu_n E \Rightarrow \boxed{\mu_n = \frac{V_{de}}{E}}$

Then  $\sigma_n E = n e \mu_n E$  ( $\because V_{de} = \mu_n E$ )

$$\therefore \boxed{\sigma_n = n e \mu_n}$$

Similarly the conductivity of holes can be written

as  $\boxed{\sigma_p = p e \mu_p}$

The total drift conductivity of a semiconductor is

$$\sigma = \sigma_n + \sigma_p$$

$$\boxed{\sigma = n e \mu_n + p e \mu_p}$$

The total drift current density  $J_{drift}$  is

given by 
$$J_{drift} = (J_n)_{drift} + (J_p)_{drift}$$

$$J_{drift} = n e \mu_n E + p e \mu_p E$$

$$\therefore \boxed{J_{drift} = e E [n \mu_n + p \mu_p]}$$

Diffusion Current:-

In addition to the drift motion of the charged carriers under the influence of the electric field, the charged carriers may also move by a process called "Diffusion".

Non Uniformity of Concentration of charged carriers produces diffusion current. When a part of a Semiconductor is illuminated with a light of sufficient energy, excess charged carriers are produced in the exposed region of the material.

Suppose the concentration of electrons and holes increases by  $\Delta n$  and  $\Delta p$  at a point in the material. These excess charged carriers may move from higher concentration region to low concentration region.

The rate of flow of electrons (or) holes is (rate of diffusion) is proportional to concentration gradient of excess carriers, according to "Fick's law".

$$\text{The rate of flow of electrons} = - \frac{\partial (\Delta n)}{\partial x}$$

$$= - D_n \frac{\partial \Delta n}{\partial x}$$

The electron charge flow constitute the electron diffusion current density ( $J_n$ )<sub>diff.</sub>

$$(J_n)_{\text{diff}} = (-e)_x - D_n \left( \frac{\partial \Delta n}{\partial x} \right)$$

$$= e D_n \frac{\partial \Delta n}{\partial x}$$

Similarly for holes,  $(J_p)_{\text{diff}} = e D_p \left( \frac{\partial \Delta p}{\partial x} \right)$

$$J_{\text{diff}} = J_n (\text{diff}) + J_p (\text{diff})$$

$$J_{\text{diff}} = e D_n \frac{\partial \Delta n}{\partial x} - e D_p \frac{\partial \Delta p}{\partial x}$$

The total current in the Semiconductor,

$$J_n = J_n (\text{drift}) + J_n (\text{diff}) \quad \& \quad J_p = J_p (\text{drift}) + J_p (\text{diff}).$$

$$\therefore J_n = E e n b_n + e D_n \frac{\partial \Delta n}{\partial x}$$

$$\text{Hence } J_p = E e p b_p - e D_p \frac{\partial \Delta p}{\partial x}$$

$$\therefore J_{\text{Total}} = J_n + J_p$$

$$\therefore J_{\text{Total}} = \left[ E e n b_n + e D_n \frac{\partial \Delta n}{\partial x} \right] + \left[ E e p b_p - e D_p \frac{\partial \Delta p}{\partial x} \right]$$

Einstein's Equation :-

The relation between the mobility  $\mu$  and diffusion coefficient  $D$  is called Einstein's equation.

-usion coefficient  $D$  is called Einstein's equation.

When a Semiconductor is illuminated with a

light of sufficient energy, excess charged carriers

are produced in the exposed region of

the material. This leads to a diffusion current,

creating an internal electric field a

drift current is set up and balances the

## Diffusion Component.

$$\text{ie } Ee \Delta n \mu_n = e D_n \frac{\partial \Delta n}{\partial y} - \textcircled{1}$$

The force on excess electrons ( $\Delta n$ ) to restore

the equilibrium,  $F = E x \Delta n e$  ( $\because F = Eq$ , where  $q = ne$ )

$$\textcircled{1} \text{ can be written as } Ee \Delta n = e \frac{D_n}{\mu_n} \frac{\partial \Delta n}{\partial y}$$

$$\text{but } Ee \Delta n = F,$$

$$\therefore \boxed{F = e \frac{D_n}{\mu_n} \frac{\partial \Delta n}{\partial y}}$$

According to kinetic theory of gases, if the concentration of the gas molecules increases by  $\Delta n$ , then the gas pressure increases by  $\Delta n kT$ .

The force corresponding to the pressure gradient

$$\text{is given by } \boxed{k_B T \frac{\partial \Delta n}{\partial y} = F}$$

By making an analogy between the excess carriers in a semiconductor and the gas molecules in a gas container,

$$k_B T \frac{\partial \Delta n}{\partial y} = e \frac{D_n}{\mu_n} \frac{\partial \Delta n}{\partial y},$$

$$\therefore k_B T = e \frac{D_n}{\mu_n} \Rightarrow \boxed{\frac{D_n}{\mu_n} = \frac{k_B T}{e}}$$

likewise for holes,

$$\boxed{\frac{D_p}{\mu_p} = \frac{k_B T}{e}},$$

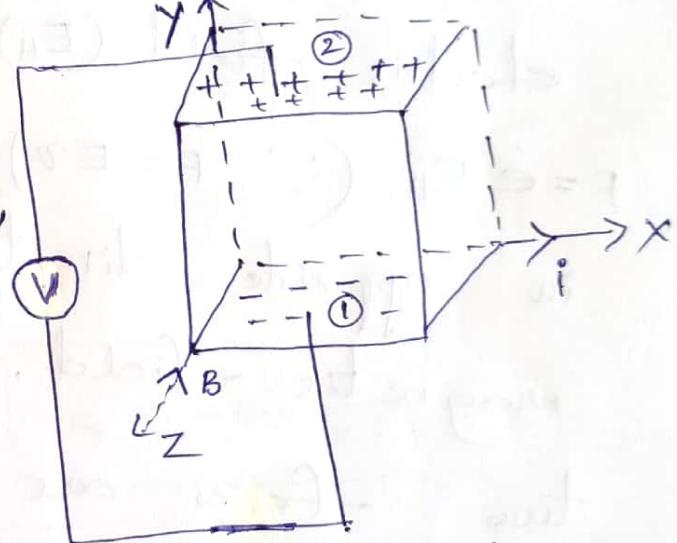
$$\therefore \boxed{\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p}}$$

is called Einstein's equation.

## Hall effect:

Statement: When a magnetic field is applied in a direction  $\perp$  to the direction of the passage of the current through a Specimen, then Voltage is developed between two faces of the Specimen in a direction  $\perp$  to both magnetic field and electric effect. This effect is known as Hall Voltage.

If the Specimen is a n-type Semiconductor, the current is passing along x-axis and a magnetic field is applied along z-axis and Voltage ( $V_H$ ) is developed between the faces along y-axis as shown in figure.



In N-type Semiconductor, the charge carriers are electrons. When a magnetic field is applied, a Lorentz force is developed

on electrons and hence they are deviated from their path and deflected towards the downward face ① and hence immediately the upward face ② is depleted by positive (+ve) charges for charge compensation. Thus a voltage ( $V_H$ ) is developed between these two faces ① and ②. This developed voltage ( $V_H$ ) produces an electric field ( $E_H$ ). This electric field ( $E_H$ ) experiences a force of  $F = e E_H$  ( $\because F = Eq$ ). This force  $E_H e$  is in opposite direction to the force due to magnetic field. At equilibrium state, the two forces are equal and hence electrons will move in a straight line path.

The force due to magnetic field ( $F_B$ ) =  $B e V_d$   
 where  $V_d \rightarrow$  drift velocity of electrons

The force due to electric field ( $F_E$ ) =  $E_H \cdot e$ .

$$\text{At equilibrium, } E_H e = B e V_d$$

$$E_H = B \cdot V_d \rightarrow ①$$

But the drift Velocity  $v_d = \frac{I}{ne}$  —②

Now put ② in ①, we get

$$E_H = B \cdot \frac{I}{ne}$$

$$\therefore E_H = B \cdot J \times \frac{1}{ne}$$

Here  $\frac{1}{ne}$  is called Hall Coefficient ( $R_H$ ).

$$\therefore E_H = B \cdot J \cdot R_H$$

$$\Rightarrow R_H = \frac{E_H}{B \cdot J} \quad \text{— ③}$$

If 'b' is the distance between two faces where ' $V_H$ ' is developed, then

$$E_H = \frac{V_H}{b} \quad (\because E = \frac{V}{d}) \quad \text{— ④}$$

and we have  $J = \frac{i}{A} = \frac{i}{b \times t} \quad \text{— ⑤}$

put ④ & ⑤ in ③, we get

$$R_H = \frac{V_H}{b \times B \times \frac{i}{b \times t}} \Rightarrow R_H = \frac{V_H \times t}{B \times i} \quad \text{— ⑥}$$

∴ Hall Coefficient  $R_H = \frac{V_H \times t}{B \times i}$  where  $t \rightarrow$  thickness of Specimen

### Applications

(i) By knowing the value of  $R_H$ , it is possible to identify the type of Semiconductor.

If  $R_H > 0 \rightarrow$  the Specimen is P-type

If  $R_H < 0 \rightarrow$  the Specimen is N-type

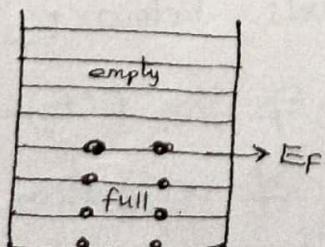
- (ii) if  $R_H$  is known, then from  $R_H = \frac{1}{ne}$ ,  
we are able to find concentration of charge  
carriers.
- (iii) If the conductivity ( $\sigma$ ) and  $R_H$  of a  
sample are known, then from  $\sigma = ne\mu$ ,  
we are able to find mobility ( $\mu$ ) of  
charge carriers.

## Fermi-Dirac distribution function:-

Pauli's exclusion principle allows a maximum no. of only two electrons in any energy level. i.e. a pair of electrons one with spin up and the other spin down occupy the lowest energy level. The next pair of electrons occupy the next energy level. This process goes on until all the electrons inside a metal occupy their positions. But there will be large no. of allowed energy levels to be filled.

The energy of highest filled state at  $T=0K$  is called Fermi energy and the energy level is known as Fermi level. It is denoted by  $E_F$ .

At  $T=0K$ , all the energy levels above  $E_F$  are empty with electrons and the energy levels below  $E_F$  are full with electrons.



When the temperature of the material is increased it receives thermal energy from surroundings and as a result the electrons are excited to higher energy levels which were unfilled at  $T=0K$ . This occupation of electrons obeys a statistical distribution law called Fermi Dirac distribution function. It is denoted by  $F(E)$ .

According to it, the probability of occupation of electrons in an energy state  $E$  is given

$$F(E) = \frac{1}{1 + e^{\frac{E - E_f}{kT}}}, \quad F(E) \rightarrow \text{Fermi Dirac function}$$

$E_f \rightarrow \text{Fermi level}$

At  $T=0K$ , Fermi Dirac distribution of electrons can be understood mathematically.

Case: 1: When  $E > E_f$ , then  $F(E) = 0$ .

i.e. all energy levels above  $E_f$  are empty with electrons.

Case: 2: When  $E < E_f$ , then  $F(E) = 1$

i.e. energy levels below  $E_f$  are full with electrons.

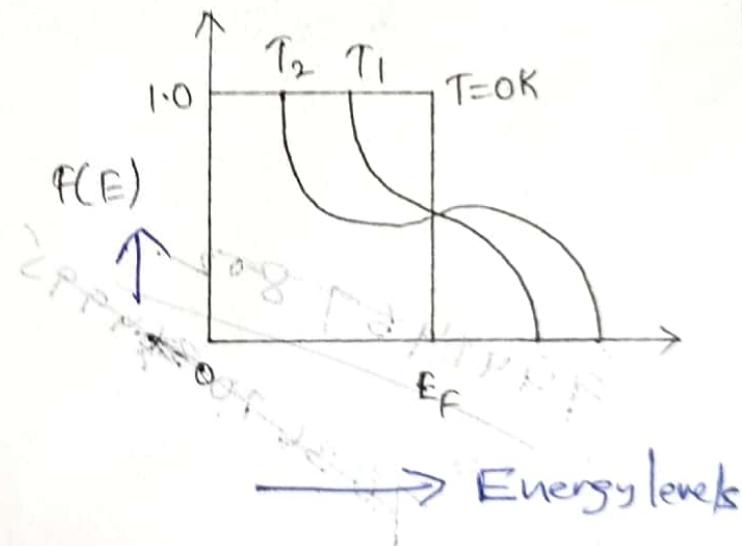
Case: 3: When  $E = E_f$ ,  $F(E) = 1/2$

Then probability of occupation of electrons in the energy levels is 50%.

Fermi Dirac distribution function Varies with temperature.

As the temperature increases the probability of occupation of electrons  $F(E)$  in the energy levels below  $E_F$  decreases and above  $E_F$  increases.

The variation F.D distribution function with temperature is as shown



## IV(A) SEMICONDUCTORS

Based on electrical conductivity, materials are divided into 3 types. They are conductors, insulators and Semiconductors. In conductors large no. of free electrons are available which are useful for the conduction mechanism. These materials have very low resistivity and very high conductivity. The resistivity of conductors is very low and lies in the range of  $10^8 \Omega\text{m}$  to  $10^{16} \Omega\text{m}$ . Cu, Ag and Au are the most important one.

In insulators, no free electrons are available, hence these are not useful for the electrical conduction mechanism. These materials have very high resistivity and almost zero conductivity. The resistivity of insulators lies in the range of  $10^8 \Omega\text{m}$  to  $10^{18} \Omega\text{m}$ .

Eg: Glass, porcelain, mica, etc.

The Semiconductors have intermediate properties of conductors and insulators. These materials behave as insulators at low temperatures and as conductors at high temperatures.

The resistivity of Semiconductors lies in the range of  $10^6 \Omega\text{m}$  to  $10^8 \Omega\text{m}$ . Elements such as Si, Ge, Se are the elementary Semiconductors. The compounds GaAs, GaP are the compound Semiconductors. The energy band diagram of a Semiconductor is similar to that of insulator, but the energy band gap is relatively small and is of the order of 1eV. The energy gap of Si is 1.1eV and for Ge, it is 0.72eV. At T=0K, the V.B is

completely full with electrons. Hence it is an insulator. However at room temperature, the thermal energy will be large enough to exceed the energy gap and a significant no. of electrons are thermally excited from the V.B to the conduction band, where they become conduction electrons. Under an applied voltage both holes as well as electrons contribute to the flow of current. Since more electrons can enter into a conduction band with more thermal excitation the conductivity of a semiconductor increases with temperature.

### Basic Definitions

#### Intrinsic Semiconductor :-

A Semiconductor which does not have any kind of impurity, behaves as an insulator, at 0K and behaves as a conductor at higher temperature is known as intrinsic Semiconductor.

Ex:- pure Ge and Si crystal.

#### Extrinsic Semiconductors :-

A Semiconductor which has either the donor impurities (or) the acceptor impurities is known as Extrinsic Semiconductor.

#### Electron - hole pair Generation :-

When a suitable form of energy is supplied to a Semiconductor, then electrons take transition from V.B to C.B. Hence, a free electron in C.B and a free hole in V.B is formed. This phenomenon is known as electron - hole pair generation.

### Recombination:

The process of combining a conduction electron with a valence hole is known as recombination. During this process, some energy, which is equal to energy gap of a semiconductor is released.

### Lifetime:

The duration of time between the process of electron-hole pair generation and recombination can be defined as lifetime. units: seconds.

### Carrier Concentration:

The no. of charge carriers per unit volume is defined as carrier concentration.

units: no. of electrons/m<sup>3</sup>.

### Electron Mobility:

It is defined as the velocity acquired by the conduction per unit electric field strength.

$$\therefore \mu_e = \frac{v}{E} \quad (\because v \propto E)$$

### Electrical conductivity of Semiconductors:-

on the basis of free electron theory, the charge carriers can be assumed to be moving freely inside a semiconductor. Both the electrons and holes contribute the conductivity of the semiconductor. let us consider to start with, the conductivity in a semiconductor due to the flow of electrons only.

Consider a semiconductor of area of cross section A, in which a current is passing through it. let 'v' be the velocity of electrons whose flow in the conductor constitutes the electric current. The electron

move through a distance 'v' in one second.

As per the assumption of free electron theory, a large no. of free electrons flow freely through the semiconductor whose area of cross-section is A.

The volume occupied by the electrons in one second

$$= A \times v$$

If ' $N_e$ ' is the no. of electrons per unit volume, 'e' is the magnitude of the charge of electron,

The total no. of electrons occupied with a volume of  $A \cdot v$  is given by  $N_e \cdot A \cdot v$ .

The charge flow per second =  $N_e \cdot A \cdot v \cdot e$  ( $\because n_v = n_e$ )

Since charge flow per second is I.

$$\therefore I = N_e A v e$$

$$\text{Current density } (J) = \frac{I}{A} = N_e v \cdot e \rightarrow (1)$$

$$\text{The electron mobility, } M_e = \frac{v}{E} \Rightarrow v = M_e \cdot E \rightarrow (2)$$

Substituting (2) in (1), we get -

$$J = N_e M_e E \cdot e \rightarrow (3)$$

But from Ohm's law,  $J = \sigma E$ ,  $\sigma \rightarrow \text{conductivity of charge carriers}$ .

If  $\sigma_e$  is the conductivity due to electrons in the semiconductor, then  $J = \sigma_e E \rightarrow (4)$

Comparing (3) and (4)

$$\sigma_e = N_e M_e e$$

Now, let us consider the contribution of holes to the conduction of electricity.

If  $\sigma_h$  is the conductivity due to holes,  $N_h$  no. of holes/unit volume and  $M_h$  is the mobility of holes, then

equation of conductivity due to holes can be written as

$$\sigma_h = N_n e M_h$$

The total conductivity of a semiconductor is given by the sum of  $\sigma_e$  and  $\sigma_h$

$$\text{i.e., } \sigma = \sigma_e + \sigma_h = N_n e M_e + N_n e M_h$$

$$\therefore \sigma = e [N_n M_e + N_n M_h]$$

For an intrinsic semiconductor, the no. of holes is always equal to the no. of electrons. Let it be equal to

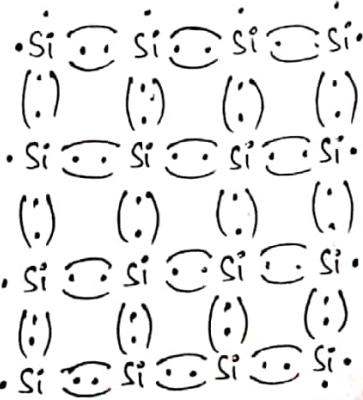
$$n_i. \quad \text{i.e. } N_n = N_h = n_i$$

$$\therefore \sigma_i = n_i e [M_e + M_h]$$

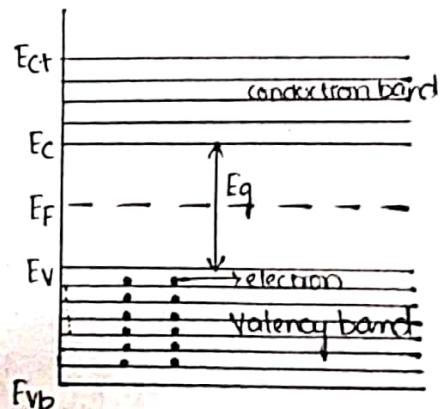
### Intrinsic Semiconductors - carrier concentration:

Pure 'Ge' and 'Si' crystal is called, intrinsic semiconductor. Each semiconductor atom possess four valence electrons in the outermost orbit. To get stability, each of these atoms has to get 8 electrons in the outermost orbit, so each atom makes four covalent bonds with the surrounding four other atoms in the crystal.

The crystal structure of 'Si' at OK is shown in fig 1(a). The band diagram of this material is shown in fig 1(b)

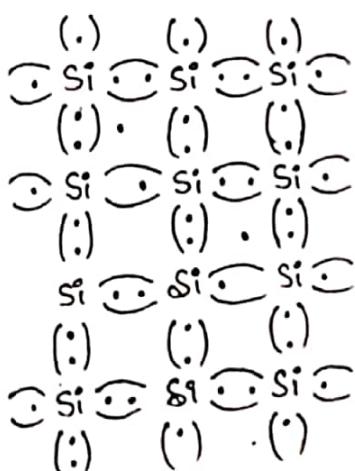


1(a) Crystal Structure of Si at 0K

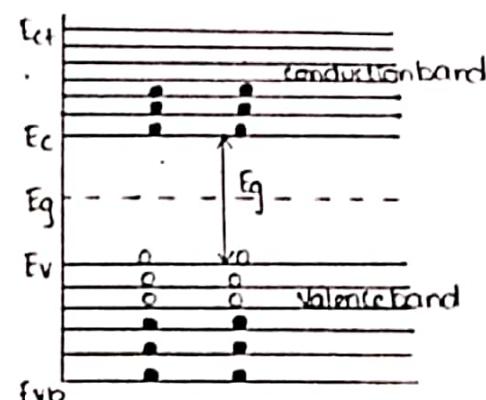


1(b) Band diagram of Si at 0K

At 0K, all the valence electrons of Si atoms are participating in covalent bonds and their energies constitute a band of energies called valence band so at 0K valence band is full and conduction band is empty of electrons. The allowed band of energies above the valence band is called conduction band. Suppose, if we raise the temperature of the semiconductor to some room temperature  $T$ K, at this temperature some of the valence electrons which are participating in covalent bonds and present in the top energy levels of valence band will take thermal energies. If the increase in thermal energy of electrons present in top energy levels of valence band is equal to or greater than the energy gap of the semiconductor, then electrons come away from the bonding and move freely inside the crystal, as shown in fig(a). These electrons possess energies equal to the lower energy levels of conduction band.



Crystal structure of Si at  $T$ =0K



Band diagram of Si at  $T$ =0K

These free electrons will participate in electrical conduction, hence the band in which these

electrons present is named as conduction band.

If an electron comes away from bonding, then that atom acquires one unit +ve charge, it participates in electrical conduction. This electron vacancy (or) electron deficiency of intrinsic Semiconductor is called hole. The electron vacancies in valence band will exist as holes in the valence band, as shown in fig 2(b). We know that in intrinsic semiconductors the charge carriers are nothing but electrons in the C.B and holes in the V.B. We have to calculate the carrier concentration namely no.of electrons in the C.B per unit volume of the material ( $n$ ) as well as no.of holes in the V.B per unit volume of the material ( $p$ ).

calculation of density of electrons :-

Let ' $d_n$ ' be the no.of electrons available between energy interval  $E$  and  $E+dE$  in the conduction band,

$$dn = Z(E) \cdot F(E) \cdot dE$$

Where  $Z(E) \cdot dE$  is the density of states at the bottom of the conduction band is given by quantum mechanics to be  $Z(E) = \frac{4\pi}{h^3} (2m_e^*)^{3/2} (E - E_c)^{1/2}$  and  $F(E)$  is the Fermi-Dirac probability function.

$$F(E) = \frac{1}{1 + \exp(\frac{E - E_F}{kT})}$$

i.e.,  $F(E)$  - probability of an electron occupying an energy state ' $E$ '

Compare to the exponential value the '1' in the denominator is negligible.

$$\text{i.e., } \exp\left(\frac{E - E_F}{k_B T}\right) \gg 1$$

$$\text{Hence } F(E) = \frac{1}{\exp\left(\frac{E - E_F}{k_B T}\right)} = \exp\left(\frac{E_F - E}{k_B T}\right)$$

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

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

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

$$\text{Let } E - E_C = x$$

$$\Rightarrow E = E_C + x$$

$$\text{As } E \rightarrow E_C \Rightarrow x \rightarrow 0$$

$$\Rightarrow dE = dx$$

$$E \rightarrow \infty \Rightarrow x \rightarrow \infty$$

$$\therefore n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} \exp\left(\frac{E_F}{k_B T}\right) \int_0^{\infty} x^{1/2} \cdot \exp\left(-\frac{(E_C + x)}{k_B T}\right) \cdot dx$$

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} \exp\left(\frac{E_F - E_C}{k_B T}\right) \int_0^{\infty} x^{1/2} \cdot \exp\left(-\frac{x}{k_B T}\right) dx$$

using  $\Gamma$  (Gamma function)

$$\int_0^{\infty} x^{1/2} \exp\left(-\frac{x}{k_B T}\right) dx = (k_B T)^{3/2} \cdot \frac{\pi^{1/2}}{2}$$

$$\text{Hence, } n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} \exp\left(\frac{E_F - E_C}{k_B T}\right) (k_B T)^{3/2} \cdot \frac{\pi^{1/2}}{2}$$

i.e., no. of electrons per unit volume of the material is given by

$$n = 2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2} \cdot \exp\left(\frac{E_F - E_C}{k_B T}\right)$$

## Calculation of holes conc. in the V.B:-

Basically hole is deficiency of electron, then the fermi function for hole is,  $1 - F(E)$ ,

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

Since  $E_V$  is the energy of the top of the valence band

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

The no. of holes present in the V.B per unit volume of the material is obtained by integrating between the limits  $E_{Vb}$  to  $E_V$ , where  $E_{Vb}$  - bottom energy level of V.B

$$\begin{aligned} \therefore n_h &= \int_{E_{Vb}}^{E_V} Z(E) \cdot (1 - F(E)) dE & E_V - \text{top energy level of V.B} \\ &= \int_{-\infty}^{E_V} [1 - F(E)] \cdot Z(E) dE + \int_{E_{Vb}}^{-\infty} [1 - F(E)] \cdot Z(E) dE \\ &= \int_{-\infty}^{E_V} [1 - F(E)] \cdot Z(E) dE - \int_{-\infty}^{E_{Vb}} [1 - F(E)] \cdot Z(E) dE \end{aligned}$$

below  $E_{Vb}$  holes will not exist. Hence it becomes

$$n_h = \int_{-\infty}^{E_F} [1 - F(E)] \cdot Z(E) \cdot dE = 0$$

$$n_h = \int_{-\infty}^{E_V} \frac{4\pi}{h^3} (2m_h^*)^{3/2} (E_V - E)^{1/2} \cdot e^{\frac{E-E_F}{kT}} \cdot dE$$

$$n_h = \frac{4\pi}{h^3} (2m_h^*)^{3/2} \cdot e^{-\frac{E_F}{kT}} \int_{-\infty}^{E_V} (E_V - E)^{1/2} \cdot e^{(E/kT)} \cdot dE$$

$$\text{Let } E_V - E = x \Rightarrow E = E_V - x \Rightarrow dE = -dx$$

As  $E \rightarrow -\infty \Rightarrow x \rightarrow \infty$ , As  $E \rightarrow E_V \Rightarrow x \rightarrow 0$

$$\begin{aligned} \int_{-\infty}^{E_V} (E_V - E)^{1/2} \cdot \exp\left(\frac{E}{kT}\right) dE &= - \int_{\infty}^0 x^{1/2} \cdot \exp\left(\frac{E_V-x}{kT}\right) dx \\ &= e^{\frac{E_V}{kT}} \int_0^{\infty} x^{1/2} \cdot e^{-\frac{x}{kT}} dx \\ &= e^{\frac{E_V}{kT}} \cdot (kT)^{3/2} \cdot \frac{\pi^{1/2}}{2} \end{aligned}$$

Hence

$$n_h = \frac{4\pi}{h^3} (2m_h^*)^{3/2} \exp\left(-\frac{E_V - E_F}{kT}\right) (kT)^{3/2} \cdot \frac{\pi^{1/2}}{2}$$

$$n_h = 2 \left( \frac{2\pi m_h^* kT}{h^2} \right)^{3/2} \exp\left(-\frac{E_V - E_F}{kT}\right)$$

This expression gives the no. of holes (or) vacancies in the V.B per unit volume.

### Intrinsic concentration:

The product of electron-hole concentration will give the intrinsic concentration of semiconductor.

$$n_e n_h = 4 \left( \frac{2\pi kT}{h^2} \right)^3 (m_e^* m_h^*)^{3/2} e^{(E_V - E_C)/kT}$$

$$\text{Let } E_C - E_V = E_g$$

for an intrinsic semiconductor,  $n_e = n_h = n_i$

$$n_i^2 = 4 \left( \frac{2\pi kT}{h^2} \right)^3 (m_e^* m_h^*)^{3/2} e^{-Eg/kT}$$

$$n_i = 2 \left( \frac{2\pi kT}{h^2} \right)^{3/2} (m_e^* m_h^*)^{3/4} e^{-Eg/2kT}$$

### Extrinsic Semiconductors

The conductivity of extrinsic semiconductors can be increased enormously by adding small amounts of impurity atoms such as pentavalent atoms like P, As, Sb, etc (or) trivalent atoms like B, Al, etc.

There are two types of extrinsic semiconductors.

- ① n-type extrinsic semiconductor
- ② p-type extrinsic semiconductor

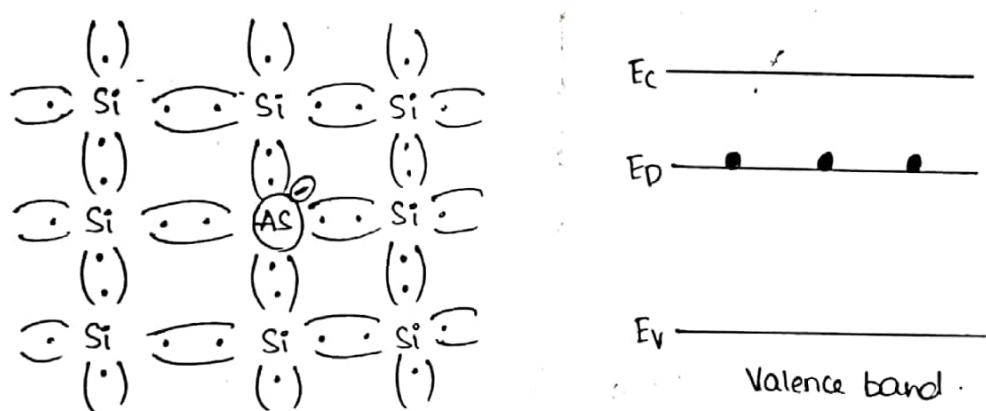
#### n-type Semiconductor :-

Pentavalent atoms such as P, As, Sb have five valence electrons in the outermost orbits when anyone such impurity is added to the intrinsic semiconductor, four electrons are participating in covalent bonding with four neighbouring pure semiconductor atoms. The fifth valence electron is weakly bound to the parent atom. Even for lesser thermal energy this fifth electron is released leaving the parent atom as positively ionised. During this process no hole is generated. Since these pentavalent atoms donate negative charges (electrons) they are called N-type impurities and the semiconductors doped with pentavalent impurities are called N-type semiconductors.

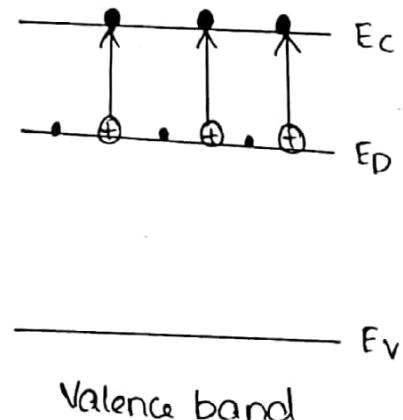
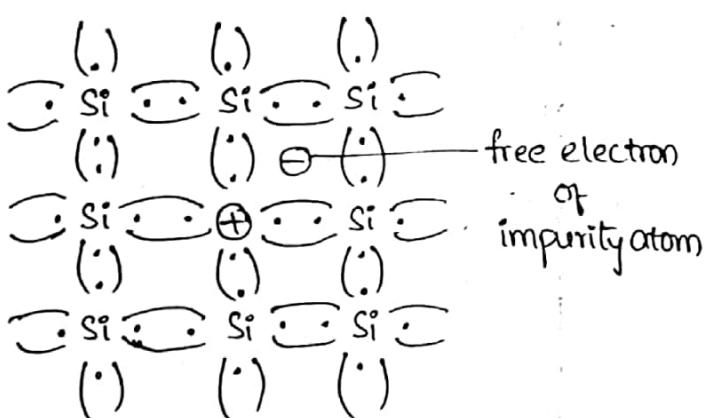
In the energy level diagram, the energy level of the fifth electron is called donor level. The donor level is so closed to the bottom of the conduction band. At room temperature most of the donor level electrons are excited into the conduction band and become majority charged carriers.

If the thermal energy is sufficiently high in addition to the ionisation of donor atoms, breaking of covalent bonds takes place and gives rise to generation of electron-hole pairs.

Hence in N-type semiconductor, the electrons are majority carriers and holes are minority carriers.



②



Valence band

→ At very low temperatures, the no. of electrons in the conduction band must be equal to the no. of ionised donor atoms.

→ If we assume that  $E_F$  lies more than a few  $kT$  above the donor level, then the density of ionised donor atoms is given by

$$N_D [1 - F(E_D)] = N_D \cdot e^{\frac{E_D - E_F}{kT}}$$

→ Density of electrons in the conduction band is given by

$$n = 2 \left( \frac{2\pi m_e^* kT}{h^2} \right)^{3/2} \cdot e^{\frac{E_F - E_C}{kT}}$$

$$\text{then } N_D \cdot e^{\frac{E_D - E_F}{kT}} = 2 \left( \frac{2\pi m_e^* kT}{h^2} \right)^{3/2} e^{\frac{E_F - E_C}{kT}}$$

Taking log on both sides:

$$\log N_D + \frac{E_D - E_F}{kT} = \log 2 \left( \frac{2\pi m_e^* kT}{h^2} \right)^{3/2} + \frac{E_F - E_C}{kT}$$

$$\log \left[ \frac{N_D}{2 \left( \frac{2\pi m_e^* kT}{h^2} \right)^{3/2}} \right] = \frac{E_F - E_C - E_D + E_F}{kT}$$

$$2E_F - (E_C + E_D) = kT \log \left[ \frac{N_D}{2 \left( \frac{2\pi m_e^* kT}{h^2} \right)^{3/2}} \right]$$

$$E_F = \frac{E_C + E_D}{2} + \frac{kT}{2} \log \left[ \frac{N_D}{2 \left( \frac{2\pi m_e^* kT}{h^2} \right)^{3/2}} \right] \rightarrow ①$$

$$\text{At } T = 0K, E_F = \frac{E_C + E_D}{2}$$

i.e., at  $T=0K$ , fermilevel lies exactly at the middle of  $E_C$  and  $E_D$ .

Density of electrons in the conduction band

We know that the density of electrons in the conduction band is given by  $n = \frac{2}{h^2} \left( \frac{2\pi m_e^* kT}{h^2} \right)^{3/2} e^{\frac{E_F - E_C}{kT}}$

Substituting ① in this equation, we get

First consider  $e^{\frac{E_F - E_C}{kT}}$

$$\text{i.e. } \exp \left[ \frac{E_d + E_C}{2kT} - \frac{E_C}{kT} + \frac{kT}{2kT} \log \frac{N_d}{2 \left( \frac{2\pi m_e^* kT}{h^2} \right)^{3/2}} \right]$$

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

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

$$= e^{\frac{E_d - E_C}{2kT}} \cdot \frac{(N_d)^{1/2}}{\left[ 2 \left( \frac{2\pi m_e^* kT}{h^2} \right)^{3/2} \right]^{1/2}}$$

Substituting this value in  $n = \frac{2}{h^2} \left( \frac{2\pi m_e^* kT}{h^2} \right)^{3/2} \cdot e^{\frac{E_F - E_C}{kT}}$ , then

$$n = \frac{2}{h^2} \left( \frac{2\pi m_e^* kT}{h^2} \right)^{3/2} \times e^{\frac{E_d - E_C}{2kT}} \cdot \frac{(N_d)^{1/2}}{\left[ 2 \left( \frac{2\pi m_e^* kT}{h^2} \right)^{3/2} \right]^{1/2}}$$

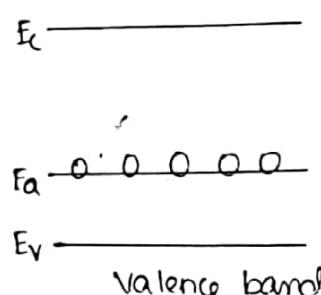
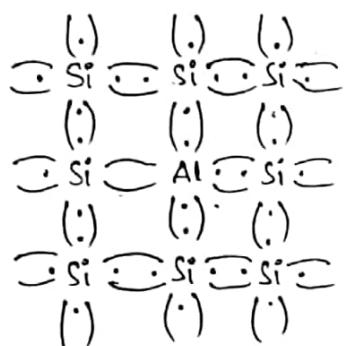
$$n = (2N_d)^{1/2} \left( \frac{2\pi m_e^* kT}{h^2} \right)^{3/4} \cdot e^{\frac{E_d - E_C}{2kT}}$$

(or)

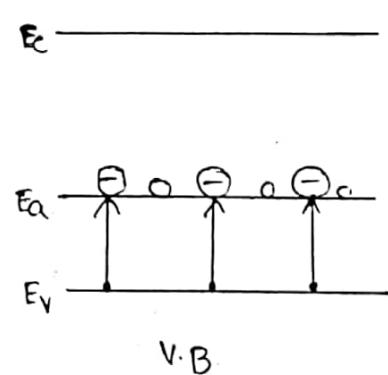
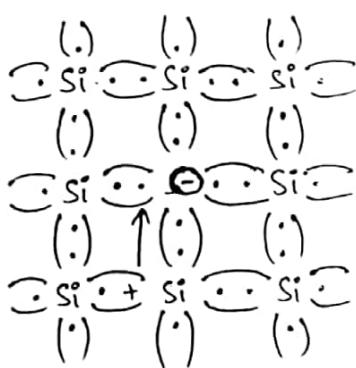
$$n = (2N_d)^{1/2} \cdot e^{\frac{E_d - E_C}{2kT}} \cdot \left( \frac{2\pi m_e^* kT}{h^2} \right)^{3/4}$$

## P-type extrinsic Semiconductors :-

Trivalent elements such as Boron, Aluminium, Gallium (or) Indium have 3 electrons in their outermost orbits. When any one such impurity is added to the intrinsic semiconductor (Ge, Si) then all the 3 electrons of impurity atom are engaged in covalent bonding with 3 neighbouring 'Si' (or) Ge atoms. Trivalent impurity atom like 'Al' needs one more electron to complete its bond. This electron may be supplied by 'Si' (or) Ge atom, thereby creating a vacant electron site (or) hole, on the semiconductor atom. Since 'Al' accepts one extra electron, the energy level of this impurity atom is called acceptor level.



(a)



(b) at  $T > 0 \text{ K}$

This acceptor level lies just above the valence band as shown in fig. These types of trivalent impurities are called acceptor impurities and the semiconductors doped with acceptor impurities are called P-type semiconductors.

At low temperatures, these acceptor atoms get ionised taking electrons from the valence band and thus giving rise to holes in the V.B for conduction. Please remember that due to ionisation of acceptor atoms only holes and no electrons are created. If the temperature is sufficiently high, in addition to the above process electron-hole pairs are generated due to breaking of covalent bonds. Thus holes are more in number than electrons and hence holes are majority carriers and electrons are minority carriers. EA represents the energy level corresponding to the acceptor impurity.

With increase of temperature acceptor atoms get ionised i.e., the electrons move from V.B and occupy the vacant sites in the acceptor energy level thereby leaving holes in the valence band. Density of holes in the V.B is given by

$$P = 2 \left( \frac{2\pi m_h^* kT}{h^2} \right)^{3/2} \cdot e^{\frac{E_V - E_F}{kT}} \quad \rightarrow ①$$

Since  $E_F$  lies below acceptor level, the density of ionised acceptor atoms is given by

$$N_A \cdot F(E_A) = N_A \cdot e^{\frac{E_F - E_A}{kT}}$$

Since the density of holes in the V.B is equal to the density of ionised acceptors,

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

Taking 'log' on both sides,

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

$$\log 2 \left( \frac{2\pi m_h^* kT}{h^2} \right)^{3/2} + \frac{E_V - E_F}{kT} = \log N_A + \frac{E_F - E_A}{kT}$$

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

$$= \frac{E_V + E_a - 2E_F}{kT}$$

$$\therefore E_F = \frac{E_V + E_a}{2} - \frac{kT}{2} \log \left[ \frac{N_a}{2 \left( \frac{2\pi m_h^* kT}{h^2} \right)^{3/2}} \right] \rightarrow ②$$

Consider

$$e^{\frac{E_V - E_F}{kT}} = \exp \left[ \frac{E_V}{kT} - \frac{(E_V + E_a)}{2kT} + \frac{kT}{2kT} \log \left( \frac{N_a}{2 \left( \frac{2\pi m_h^* kT}{h^2} \right)^{3/2}} \right) \right]$$

$$\therefore e^{\frac{E_V - E_F}{kT}} = \exp \left[ \frac{E_V - E_a}{2kT} + \log \left[ \frac{N_a}{2 \left( \frac{2\pi m_h^* kT}{h^2} \right)^{3/2}} \right]^{1/2} \right]$$

$$e^{\frac{E_V - E_F}{kT}} = e^{\frac{E_V - E_a}{2kT}} \cdot \frac{N_a^{1/2}}{\left[ 2 \left( \frac{2\pi m_h^* kT}{h^2} \right)^{3/2} \right]^{1/2}}$$

Substituting this value in ①, we get

$$P = 2 \left( \frac{2\pi m_h^* kT}{h^2} \right)^{3/2} \times e^{\frac{E_V - E_a}{2kT}} \cdot \frac{(N_a)^{1/2}}{\left[ 2 \left( \frac{2\pi m_h^* kT}{h^2} \right)^{3/2} \right]^{1/2}}$$

$$\therefore P = \left[ 2 \left( \frac{2\pi m_h^* kT}{h^2} \right)^{3/2} \right]^{1/2} (N_a)^{1/2} \cdot e^{\frac{E_V - E_a}{2kT}}$$

$$\therefore P = (2N_a)^{1/2} \cdot e^{\frac{E_V - E_a}{2kT}} \cdot \left( \frac{2\pi m_h^* kT}{h^2} \right)^{3/4}$$

An electronic device which has 2 electrodes is known as a diode  
('di' means two and 'ode' means electrode)

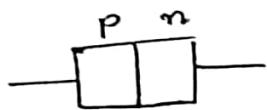
Semiconductor diode or p-n junction:-

If a p-type semi cond. is suitably joined to an n-type " ", then the combination is known as a semi. cond. diode or p-junction or junction diode or crystal diode.

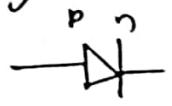
The methods of preparing p-n junctions are

- Crowth type
- Slab type
- Sintering type

The schematic representation of a junction diode is as shown below.



The circuit symbol or representation of a junction diode is.



In this the arrow head represents the p-type material and bar represents the n-type material.

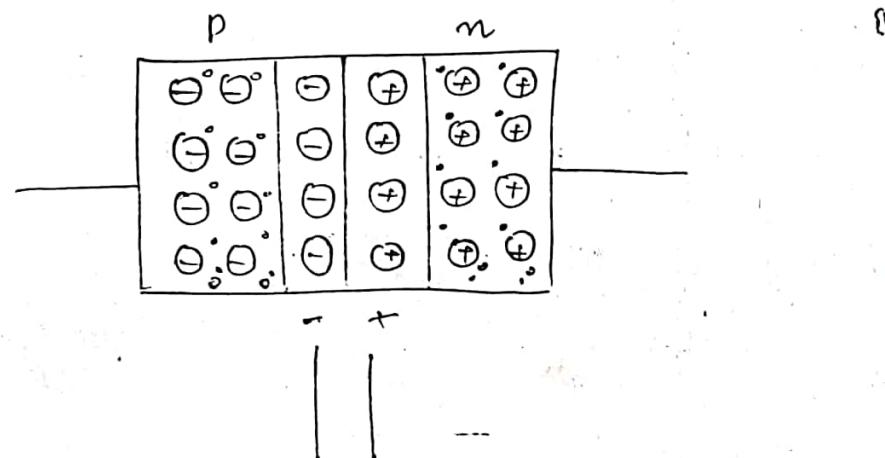
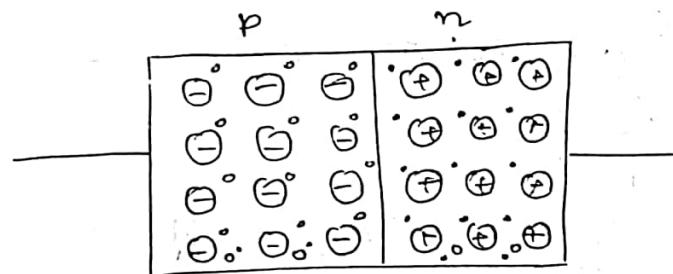
The arrow head also gives an idea about

→ the direction of the conventional current

### Depletion Region:

Consider a p-n junction diode as shown in the fig.

The p-type semiconductor consists of holes as majority charge carriers, free electrons as minority charge carriers and the negative ions of the trivalent impurity (as immobile charge carriers). The n-type semiconductor consists of free electrons as majority charge carriers and the positive ions of the pentavalent impurity (as immobile charge carriers).



The concentration of holes is more in p-type semiconductor than in n-type semiconductor and conc. of free electrons is more in n-type semiconductor than in p-type semiconductor.

Due to this diff. in conc. the holes cross the junction from p-type to n-type and the free electrons cross the junction from n-type to p-type. This phenomenon is known as diffusion of charge carriers.

At the beginning the holes and the free electrons cross the junction across the junc. and they combine each other. This phenomenon is known as recombination. Due to the recombination some region on either side of the junction is depleted (emptied off) mobile charge carriers (holes and free electrons).

This region which is depleted of mobile charge carriers is known as depletion region or depletion layer or transition region.

The thickness of the depletion region is of the order of microns ( $10^{-6}$  m). Due to the formation of depletion layer a barrier will be developed

across the junction which prevents further flow of the holes & free electrons across the junction. This barrier is known as potential barrier.  
The barrier potential is -0.2 volt for Ge diode and -0.72 volt for Si diode.  
(Negative potential boundaries allow the charges to pass)

Note- Depletion region does not consist of mobile charge carriers.

Depletion region consists of immobile

(positive ions of pentavalent impurity in n-type semiconductor & negative ions of trivalent impurity of p-type semiconductor).

(p-type electrons ~~and~~ <sup>are</sup> negative ions of silicon)

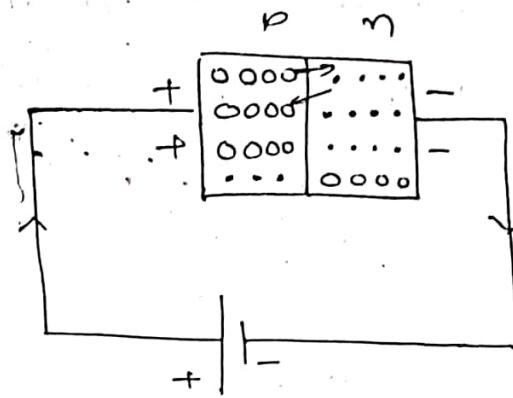
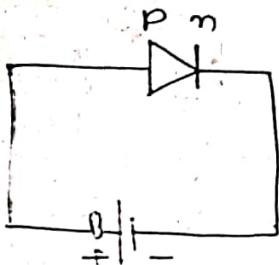
### Biassing:

Connecting the electrodes of a diode to the terminals of a battery is known as biassing. The purpose of biassing is either to increase or to decrease the width of the depletion layer.

### Forward Biassing:

If p-type semi-conductor of a semi-conductor diode is connected to the positive terminal of the battery & n-type semi-conductor is connected to negative terminal of the battery then the diode is said to be forward biassed.

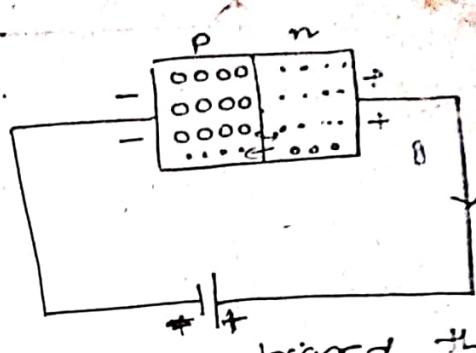
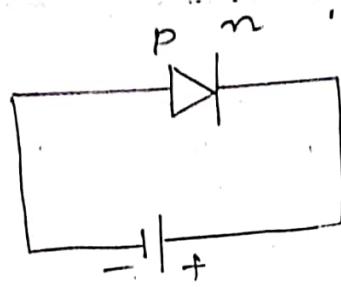
forward biased.



- 2. when the diode is forward biased the width of depletion layer decreases.
- 3. In a forward biased diode the holes cross the junction from p to n & free electrons cross the junction from n to p.
- 4. The dir. of the current in a forward biased diode is from p-type to n-type
- 5. The current in a f.b. diode is due to majority charge carriers (holes & f.e's)
- 6. The resistance of a fb-diode is very low  $\approx$  the order of 10 ohms.
- 7. The resistance of an ideal diode in forward biasing is 0.

### Reverse Biasing:-

- 1. If the p-type semicond. is connected to 've' terminal & n-type " " " " +ve " of the battery then the diode is said to be reverse biased.



2. When a diode is reverse biased the width of the depletion layer increases.
  3. In a reverse biased diode the majority charge carriers do not cross the junction whereas the minority charge carriers cross the junction. (The minority free  $e^-$  moves the junction from p to n and the minority holes move the junction from n to p).
  4. The drift current g.b. biased is from n-type to p-type.
  5. The current in a.b. biased is due to minority charge carriers. A small constant current passing through the diode due to minority charge carriers when it is reverse biased is known as Reverse saturation current or leakage current.
  6. The resistance of a reverse biased diode is very high and is of the order of  $10^4$  ohms.
  7. The resistance of an ideal diode when it is reverse biased is infinity.
- Diode can be used as an amplifier and a detector.

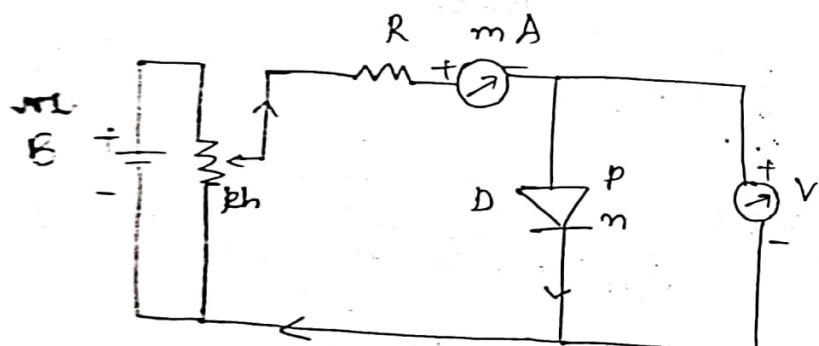
Ampere (Voltage - current)

characteristics of a semiconductor diode

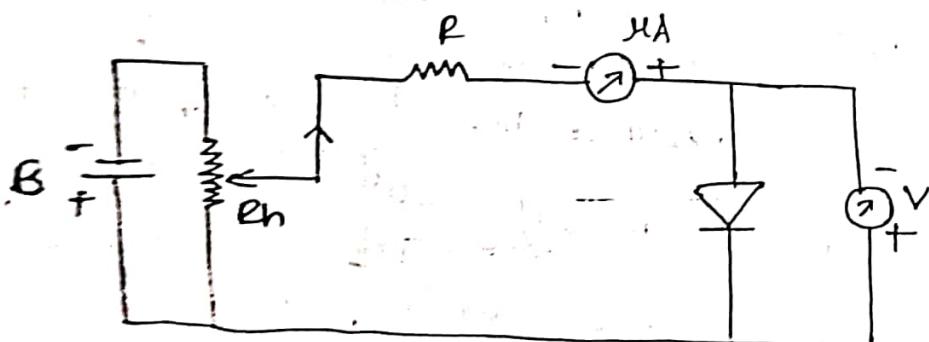
A graph drawn by taking the voltage across the diode along x-axis and the current through the diode along y-axis is known as diode characteristic.

Circuit diagram:

The circuit diagrams used to study the diode characteristics in forward & reverse biasing are as shown below.



Forward Biasing



Reverse Biasing

In the above circuit diagrams B is a battery (power supply),  $R_h$  is a rheostat, D is semiconductor diode, and R is a resistor.

In the case of forward biasing a milliammeter is used to measure current passing through diode and in case of reverse biasing, a microammeter is used to measure the strength of current through diode. A voltmeter V is used to measure the voltage across the diode.

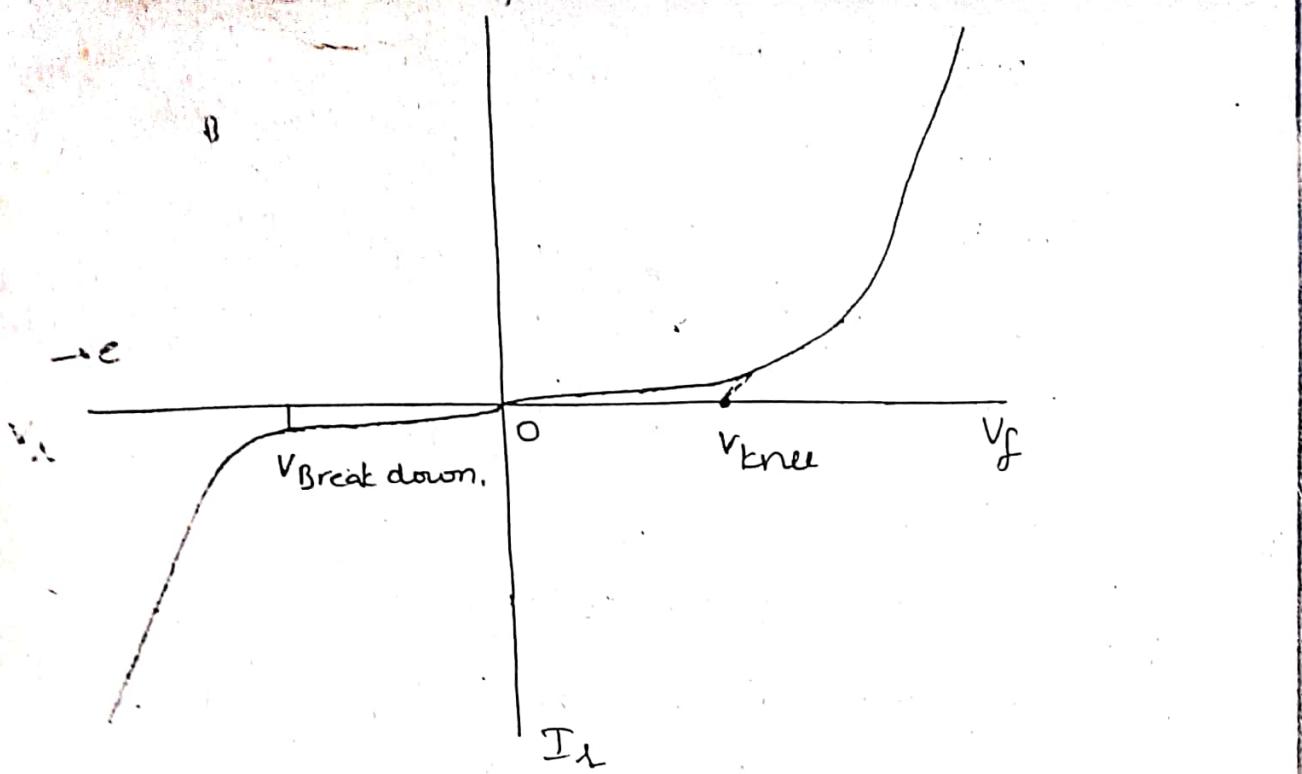
In forward biasing, the p-type material is connected to the terminal + n-type material " " is " " of the battery, whereas in reverse biasing the polarities are reversed.

### Explanation:-

The diode characteristic is as shown in the fig.

Case(i) When the diode is not biased,  $V=0$  &  $i=0$ . This is represented by point 'O' in the graph.

Case(ii) When the diode is forward biased, with the increase in the forward voltage the current through the diode almost remains zero initially.



above this voltage the current increases exponentially with the increase in the forward voltage.

Def- The forward voltage applied to the diode upto which the current almost remains zero is known as knee voltage or threshold or cut-in voltage ( $V_{knee}$ )

Ques when the diode is reverse biased, with increase in reverse voltage the current through the voltage almost remains same & is equal to the reverse saturation current. If the reverse voltage across the diode is further increased, the current increases,

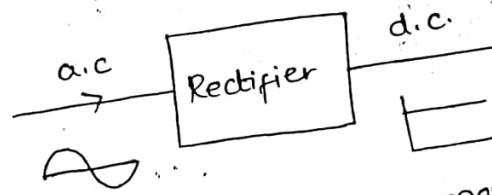
enormously and the junction heats and breaks. This reverse voltage applied to the diode above which the junction <sup>breaks</sup> is known as breakdown voltage or cut off voltage.

### Rectifier:-

### (RECTIFIER DIODE)

An electronic device which converts alternating current to direct current is known as a rectifier and the process is known as rectification.

A semiconductor diode acts as a rectifier.



Rectifiers are of two types namely half wave rectifier and full wave rectifier.

### Half wave rectifier:-

A device which allows the positive half cycles of the input A.C. and suppresses the negative half cycles is known as a half wave rectifier.

