

# Unit 1

## Crystal Structure:

- (i) Crystalline Solids → atoms are arranged in regular manner.
- (ii) Amorphous Solids → atoms are arranged randomly.

⇒ Solids are divided into two categories:

- ① Crystalline Solids
- ② Amorphous Solids

Crystalline Solids: Those solids in which the particles arranged in a regular repeating 3-dimensional lattice is known as crystalline solid.

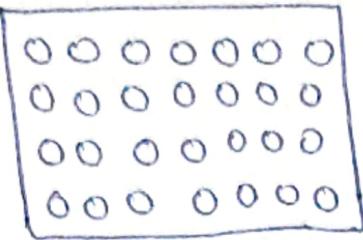
They have sharp melting point

for ex. % NaCl, diamond, Quartz etc

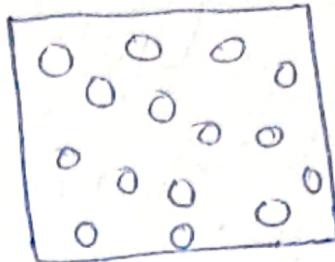
Amorphous Solids: Those solids in which particles are arranged randomly or in a irregular manner in 3-dimensional lattice is known as amorphous solid.

They melt over a range of temperature.

e.g. % Glass, Plastic etc.



[Crystalline Solid]

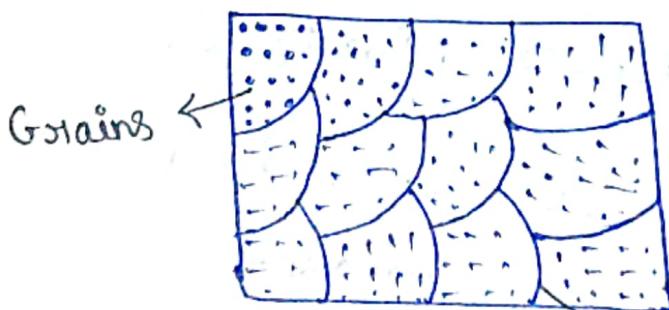


[Amorphous Solid]

Poly-crystalline Solids is a type of crystalline solid which made up of many crystals or grains known as polycrystalline solids.

Grains are separated by a boundary known as Grain boundary.

Grains are randomly oriented with respect to each other for ex. common metal, many ceramics, rocks etc are the example.

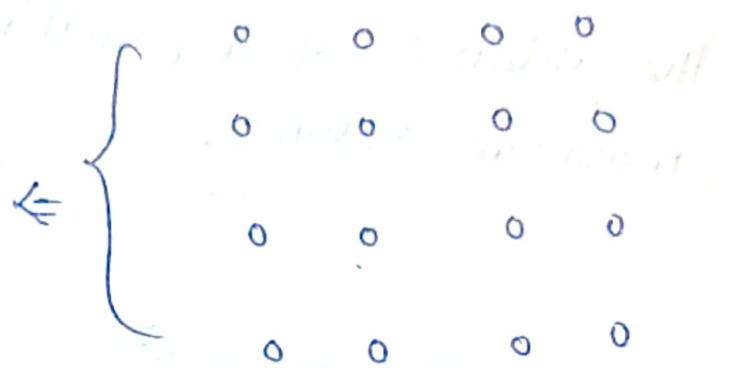


→ Poly-crystalline Solid  
e.g. rock.

[Polycrystalline Solid] → Grain boundary

⇒ Orientation are same (of atom) in each crystal but when we compare to other here. Then it is different.

Space Lattice : Space lattice is a three dimensional ordered array of points describing the arrangement of particle has identical surrounding.



Basis or Motif : Basis may be atom or group of atom present in the crystal, when Basis is attached to every lattice point a crystal structure is formed.

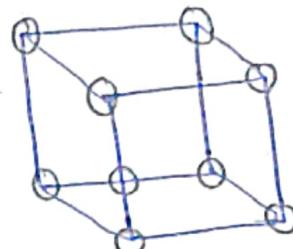
Crystalline Structure : when lattice and basis join together crystal structure is formed.



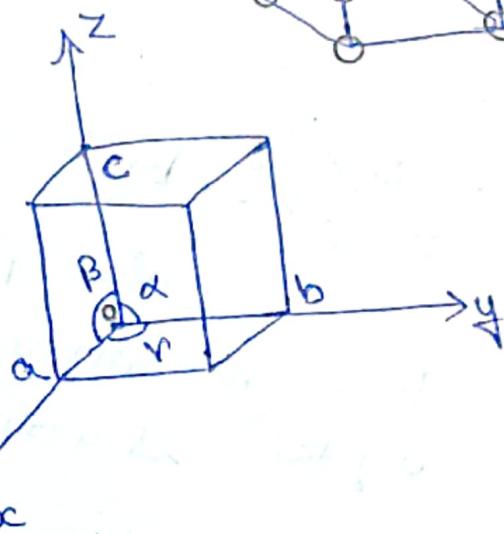
Unit Cell : Unit cell is the basic building of crystal which one repeated again and again in different directions in space, forms the entire crystal lattice or crystal structure.

Primitive Cell :- when the atoms on the lattice points are present only at the corners of unit cell, then the unit cell is called Primitive cell.

The volume of a primitive cell has a minimum volume.



### Lattice Parameters



④ Crystallographic axis  
( $0x, 0y, 0z$ )

- ⑤ Edges  
( $a, b, c$ )
- ⑥ Interfacial angles  
( $\alpha, \beta, \gamma$ )

The shape of the unit cell depends on edges and angles between them.

Crystallographic axis :- The imaginary line parallel to the edges of the unit cell which are not lying in the same plane is called crystallographic axis.

In diagram  $0x, 0y, 0z$  are crystallographic axis in the

Interfacial Angle: The angle between the edges of crystallographic axis is known as interfacial angles.

Here,  $\alpha, \beta, \gamma$  are the interfacial angles and  $a, b, c$  are the intercept of edges.

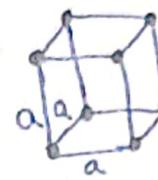
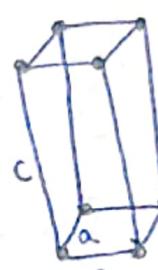
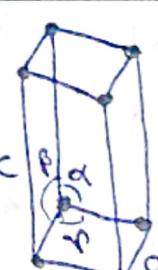
### Crystal System & Bravais Lattice:

There are seven types of crystal depending upon their interfacial angle and edges ratio.

Bravais shows that they give rise to 14 type of space lattice due to simple cubic, body centered, face centered, base centered type.

### The Seven Crystal System are:

- ① Cubic
- ② Tetrahedral
- ③ Ortho-rhombic
- ④ Trigonal (Rhombohedral)
- ⑤ Hexagonal
- ⑥ Monoclinic
- ⑦ Tri-clinic

	Crystal System	Axial Relationship	Interaxial Angle	Bravais Lattice	Unit Cell Geometry
①	Cubic	$a=b=c$	$\alpha=\beta=\gamma=90^\circ$	Simple cubic, body centered, face centered	
②	Tetrahedral	$a=b \neq c$	$\alpha=\beta=\gamma=90^\circ$	Simple cubic, body centered	
③	Orthorhombic	$a \neq b \neq c$	$\alpha=\beta=\gamma=90^\circ$	Simple cubic, body centered, base centered, face centered	
④	Monoclinic	$a \neq b \neq c$	$\alpha=\gamma=90^\circ \neq \beta$	Simple cubic, base centered	
⑤	Triclinic	$a \neq b \neq c$	$\alpha+\beta+\gamma \neq 90^\circ$	Simple cubic	
⑥	Hexagonal	$a=b \neq c$	$\alpha=\beta=90^\circ, \gamma=120^\circ$	Simple cubic	
⑦	Rhombohedral (or Trigonal)	$a=b=c$	$\alpha=\beta=\gamma \neq 90^\circ$	Simple cubic	

## Types of cubic crystals : (three types)

- ① Simple Cubic Crystal (SCC)
- ② Body centered Cubic Crystal (BCC)
- ③ Face centered cubic crystal (FCC)

### Simple cubic cell (SCC) :

In simple cubic cell, the lattice points are situated at the corners of the unit cell.

(total) No. of atoms in SCC : Number of atom

$$\text{in SCC} = 8 \times \frac{1}{8} = 1 \text{ atom per unit cell.}$$

### Coordination Number

The coordination number is defined as the number of

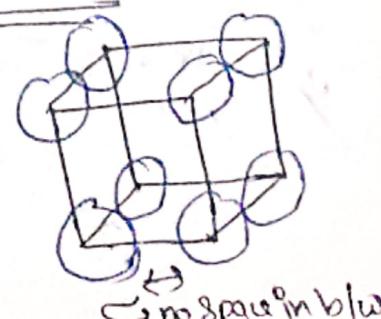
equidistant neighbours around an atom in the crystal.

In SCC unit cell, there are 6 equidistant neighbouring atom corresponding to each atom. Therefore, coordination number for SCC is 6.

⇒ The relation between atomic radius ( $r$ ) and edge length ( $a$ ) :

In 2-dimension of SCC from the diagram,

$$2r = a \Rightarrow r = \frac{a}{2}$$



## Atomic Packing factor for FCC %

It is the ratio , volume occupied by atoms in unit cell to the total volume of unit cell.

then, APF =  $\frac{\text{Total volume occupied by unit cell (of atom)}}{\text{Volume of unit cell.}}$

$$\text{APF} = \frac{\text{No. of atoms} \times \text{Volume of 1 atom}}{\text{Volume of unit cell.}}$$

atomic  
Packing factor

$$\text{APF} = \frac{1 \times \frac{4}{3} \pi r^3}{a^3} = \frac{\frac{4}{3} \pi r^3}{(2r)^3} = \frac{\pi}{6}$$

$$\text{APF.} = 0.52$$

$\therefore 52\%$  of the unit cell occupied by atom.

## Body Centered Cubic cell (BCC) %

In Body centered cubic cell, 8 atoms are present at corners of unit cell and

1 atom is present at centre of the unit cell.

$\Rightarrow$  Then, Total number of atom per unit cell

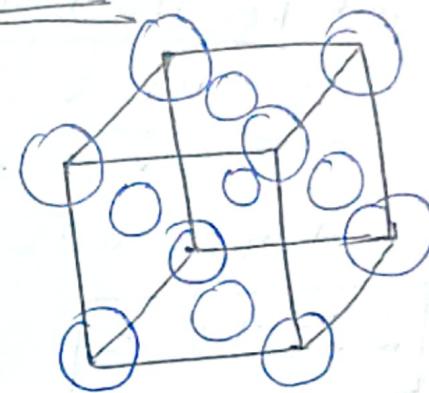
$$= \frac{1}{8} \times 8 + 1 = 2 \text{ atom / unit cell.}$$

⇒ The centre atom of BCC unit cell is equidistant from the corner atoms. So, its coordination number is 8.

Relation between  $\pi$  and  $a$ :

$$4\pi = a\sqrt{3}$$

$$a = \frac{4\pi}{\sqrt{3}}$$



APF (atomic packing factor) of BCC:

$$\text{APF} = \frac{\text{No. of atom} \times \text{Volume of 1 atom}}{\text{Volume of unit cell.}}$$

$$\text{APF} = \frac{2 \times \frac{4}{3}\pi r^3}{a^3} = \frac{\frac{8}{3}\pi r^3}{2 \times 8 \times 4r^3} \times 8\sqrt{3} = 0.68$$

APF = 0.68 ∴ 68% of unit cell occupied by atom.

Face centered cubic crystal:

In face centered cubic cell, 6 atoms are present at the face centre and 8 atoms are present at the corners of unit cell.

⇒ than total number of atom per unit

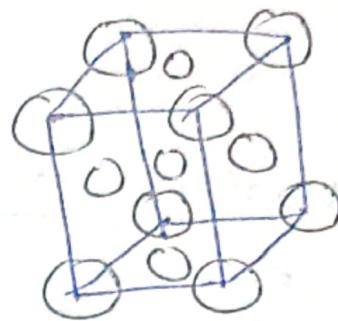
$$\text{cell} = \frac{1}{2} \times 6 + \frac{1}{8} \times 8 = 4 \text{ atom/unit cell.}$$

$\Rightarrow$  There are 12 nearest neighbouring atom to face centered atom in fcc, hence its coordination number is 12

$\Rightarrow$  and Relation b/w  $r_1$  and  $a$

$$4r_1 = a\sqrt{2}$$

$$2\sqrt{2}r_1 = a$$



$\Rightarrow$  (APF) atomic packing factor in BCC

$$\text{APF} = \frac{\text{no. of atom} \times \text{volume of atom}}{\text{volume of 1 unit cell}}$$

$$\text{APF} = \frac{4 \times \frac{4}{3}\pi r_1^3}{a^3} = \frac{2 \times \frac{8}{3}\pi r_1^3}{8 \times 2\sqrt{2}r_1^3} = \frac{\pi}{3\sqrt{2}}$$

$$\text{APF} = \frac{\pi}{3\sqrt{2}} = 0.74$$

$\Rightarrow$   $\therefore$  74% of the unit cell is occupied by the atom.

Relation between lattice constant ( $a$ ) and density ( $\rho$ ) ?

→ Volume of unit cell =  $a^3$

→ If  $\rho$  is the density of unit cell, then its mass is equal to :

$$\text{mass} = \rho a^3 \quad \text{--- (1)}$$

of unit cell

→ Now, mass of each atom in unit cell =  $\frac{M}{N_A}$

→ if there 'n' no. of atoms in unit cell,

$$\text{then mass of unit cell} = n \frac{M}{N_A} \quad \text{--- (2)}$$

→ equating (1) & (2),

$$\rho a^3 = n \frac{M}{N_A} \Rightarrow a^3 = \frac{n M}{\rho N_A}$$

Ans: Calculate the number of atoms per unit cell of a metal with lattice parameter  $2.9 \text{ \AA}$ , given molecular weight is 55.85 and density is  $7870 \text{ kg/m}^3$ .

(2)

$$\text{Sol:} \quad \text{as } a^3 = \frac{n M}{\rho N_A} \Rightarrow n = \frac{a^3 \rho N_A}{M}$$

$$n = \frac{(2.9 \times 10^{-10})^3 \times 7870 \times 10^3 \times 6.023 \times 10^{23}}{55.85}$$

$$n = 2.069 \approx 2 \text{ atom/unit cell}$$

Ques: Germanium crystallizes in diamond structure with 8 atom per unit cell. If lattice constant is  $5.6 \text{ \AA}$  and molecular weight is 72.59, calculate its density. (5492)

Sol:  $n = 8, a = 5.6 \text{ \AA}, M = 72.59 \text{ g/mol}$

$$\text{as } a^3 = \frac{nM}{\rho N_A} \Rightarrow \rho = \frac{nM}{a^3 N_A}$$

$$\rho = \frac{8 \times 72.59}{(5.6 \times 5.6 \times 5.6) \times 10^{-30} \times 6.023 \times 10^{23} \times 10^3} \approx 5492 \text{ kg/m}^3$$

for  $\text{kg/m}^3$

Ques: A substance with face centered cubic lattice has density  $6250 \text{ kg/m}^3$  and molecular weight 60.2, calculate the lattice constant (4  $\text{\AA}$ )

Sol:  $\rho = 6250 \text{ kg/m}^3, M = 60.2$

$$2 n = 4, a = ?$$

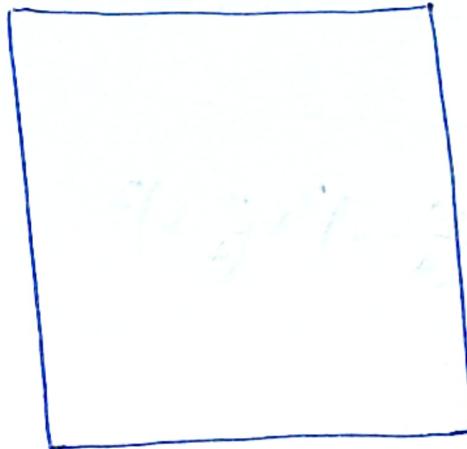
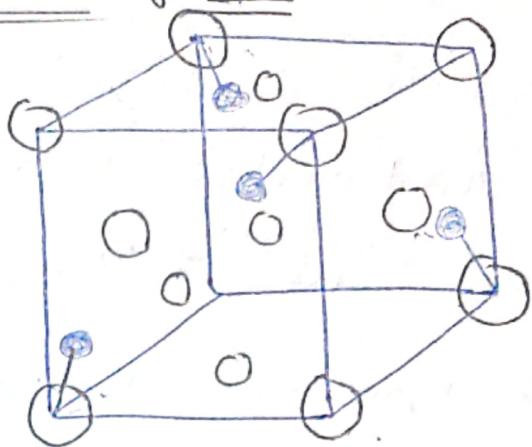
$$\text{as } a^3 = \frac{nM}{\rho N_A}$$

$$a = \left[ \frac{4 \times 60.2}{(6250 \times 10^3) (6.023 \times 10^{23})} \right]^{1/3}$$

$$a = 3.999 \times 10^{-10} \approx 4 \text{ \AA}$$

## Structure of Diamond Crystal :

- ⊗ Structure  $\Rightarrow$  FCC
- ⊗ Total atoms involved = 18
- ⊗ Type of atom = 2
  - (i) at  $(0,0,0)$ , FCC
  - (ii) at  $(\frac{1}{4}, \frac{1}{4}, \frac{1}{4})$   $\rightarrow$  (in tetrahedral shape)
- ⊗ Coordination number = 4
- ⊗ no. of atoms per unit cell = 8
- ⊗



- $\Rightarrow$  Diamond structure is face centered cubic lattice.
- $\Rightarrow$  unit cell of diamonds contain 18 atom.
  - 8 atoms are placed at corners of the cube.
  - 6 atoms are placed at each face of the cube.
  - and 4 inside it.

⇒ Basis of carbon atom consist of 1 lattice point having 2 atoms placed at  $(0,0,0)$  and at  $(\frac{1}{4}, \frac{1}{4}, \frac{1}{4})$

⇒ Total number of atoms of diamond per unit cell

$$\text{cell} = \left(\frac{1}{8} \times 8\right) + \left(\frac{1}{2} \times 6\right) + 4 = 8 \text{ atoms / unit cell}$$

⇒ Diamond structure has tetrahedron shape of carbon atoms which means that each carbon atom is attached with four carbon atoms in tetrahedron shape.

⇒ The coordination number of diamond structure is 4.

Relation between lattice constant 'a' and 'r'

$$2r = \sqrt{\left(\frac{a}{4} - 0\right)^2 + \left(\frac{a}{4} - 0\right)^2 + \left(\frac{a}{4} - 0\right)^2}$$

$$2r = \frac{\sqrt{3}a}{4}$$

$$r = \frac{\sqrt{3}a}{8}$$

Atomic packing factor %

$$\text{APF} = \frac{\text{no. of atom} \times \text{volume of 1 atom}}{\text{Volume of unit cell}}$$

$$APF = \frac{8 \times \frac{4}{3}\pi r^3}{a^3} = \frac{8 \times \frac{4}{3}\pi r^3 \times 3\sqrt{3}}{64 \times 8} = \frac{r^3 \times 3\sqrt{3}}{16}$$

$$\therefore APF = \frac{\sqrt{3}\pi}{16} = 0.340$$

$\therefore$  34% of unit cell is covered by atom.

Ques: Lattice constant of BCC crystal is 0.36 nm. calculate its atomic radius.

$$\text{Sol: } \sqrt{3}a = 4r \Rightarrow r = \frac{\sqrt{3} \times 0.36}{4} \text{ nm}$$

$$r = 0.15 \text{ nm}$$

Ques: Copper is fcc whose atomic radius is  $1.26 \times 10^{-10}$  m. calculate its lattice constant.

$$\text{Sol: } a\sqrt{2} = 4r \Rightarrow a = \frac{4 \times 1.26 \times 10^{-10}}{\sqrt{2}} = 3.56 \times 10^{-10} \text{ m}$$

Ques: which of the following an amorphous material?

- (A) Mica ~~(B)~~ Lead ~~(C)~~ Rubber ~~(D)~~ Glass

Ques: The unit cell of certain type of crystal is defined by three vectors. a, b, c. these vectors are mutually perpendicular but  $a \neq b \neq c$ . The crystal structure is?

- (A) Triclinic ~~(B)~~ Tetragonal ~~(C)~~ Orthorhombic  
(D) Monoclinic

Ques ③ Which of the following is correct sequence of the crystal structure with respect to percentage of voids (SCC - simple cubic, BCC - body centered, FCC - face centered).

(A) SCC < FCC < BCC

~~(B)~~ FCC < BCC < SCC

(C) SCC < BCC < FCC

(D) More than one of the above.

(E) None than one of the above.

Ques ④ % Packing efficiency of the body centered crystal is

~~(A)~~ 0.68      (B) 0.74      (C) 0.50      (D) 1.00

Ques ⑤ If the atomic radius of aluminium is  $r_1$ , what is the unit cell volume.

(A)  $\left(\frac{2r_1}{\sqrt{2}}\right)^3$     ~~(B)~~  $\left(\frac{4r_1}{\sqrt{2}}\right)^3$     (C)  $\left(\frac{2r_1}{\sqrt{3}}\right)^3$     (D)  $\left(\frac{2r_1}{\sqrt{5}}\right)^3$

Ques ⑥ Coordination number for FCC crystal is

(A) 4

(B) 8

~~(C)~~ 12

(D) 16

Ques ⑦ If atom is assumed to be hard sphere, the maximum value of APP in metals will be

- (A) 0.65 (B) 0.74 (C) 0.85 (D) 0.98

Ques ⑧ The crystal structure of cementite ( $\text{Fe}_3\text{C}$ ) is

- (A) FCC (B) BCC (C) Tetragonal (D) Orthorhombic

Ques ⑨ The effective number of lattice points in the unit cell of Scs, Bcc and fcc lattices respectively is

- (A) 1, 2, 3 (B) 1, 2, 4 (C) 4, 2, 1 (D) 3, 2, 1

Ques ⑩ The coordination number of fcc is

- (A) 4 (B) 8 (C) 12 (D) 16

Ques ⑪

(A) Assertion : Solids have definite mass, volume & shape.

Reason (R) : Solids can be classified as crystalline and amorphous.

~~(A)~~ Both (A) & (R) are correct and (R) is correct explanation of the (A).

(B) Both (A) & (R) are correct statements, but (R) is not correct explanation of (A).

(C) (A) is correct but (R) is incorrect.

(D) (A) is incorrect, but (R) is correct.

Ques 12 & Assertion (A) :- Solids have definite mass, volume and shape.

✓  
repeated  
written

Reason (R) :- Solids can be classified as crystalline and amorphous.

~~(a)~~ Both Assertion (A) and Reason (R), are correct statement, and (R) is correct explanation of A.

(b) both (A) & (R) are correct but (R) is not correct explanation of (A).

(c) (A) is correct, but (R) is incorrect statement

(d) (A) is incorrect but (R) is correct statement

Ques 13 & (A) assertion :- Packing efficiency of body centered cubic structure is 68%.

(R) Reason :- 68% is the maximum packing efficiency any crystal can have.

(a) both (A) & (R) are true and (R) is correct explanation of (A).

(b) both (A) and (R) are true but (R) is not correct explanation of (A)

~~(c)~~ (A) is true but (R) is false

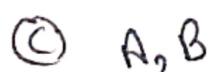
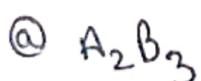
(d) (A) and (R) is false.

Ques 14 & (A) assertion :- Glass panes fixed to windows or doors of old building are slightly thicker at the bottom than at the top.

(a) Glass is a pseudo solid or supercold liquid.

- ~~(A)~~ both (A) and (R) are true and (R) is correct explanation of (A). ✓
- (B) both (A) and (R) are true but (R) is not correct explanation of (A)
- (C) (A) is true but (R) is false
- (D) both (A) & (R) are false.
- Ques(5) :- (A) Assertion :-  $\text{CsCl}$  has body-centered cubic arrangement
- (B) Reason :-  $\text{CsCl}$  has one and  $\delta\text{-Cl}^-$  in unit cell.
- ~~(A)~~ both (A) and (R) are true and (R) is correct explanation of (A).
- (B) both (A) and (R) are true and (R) is not correct explanation of (A).
- (C) (A) is true but (R) is false.
- (D) both (A) and (R) are false.

Ques(16) :- In a face-centered cubic lattice, atom A occupies the corner positions and atom B occupies the face center positions. If one atom of B is missing from one of the face centered points, the formula of the compound is :-



$$\left. \begin{array}{l} \text{atom of A} = 1 \\ \text{atom of B} = 5/2 \\ \therefore \text{A B}_{5/2} \end{array} \right\}$$

Ques 17 In a monoclinic unit cell, the relation of sides and angles are respectively.

(a)

$a \neq b \neq c$  and  $\alpha \neq \beta \neq \gamma \neq 90^\circ$



(b)

$a \neq b \neq c$  and  $\beta = \gamma = 90^\circ \neq \alpha$

(c)

$a = b \neq c$  and  $\alpha = \beta = \gamma = 90^\circ$

(d)

$a \neq b \neq c$  and  $\alpha = \beta = \gamma = 90^\circ$

Ques 18 All of the following share the same crystal structure except

(a) RbCl

(b) CsCl

~~(c) LiCl~~

(d) NaCl

Ques 19 Ammonium chloride crystallizes in a body centered cubic lattice with edge length of unit cell of 390 pm. If the size of chloride ion is 180 pm, the size of ammonium ion would be:-

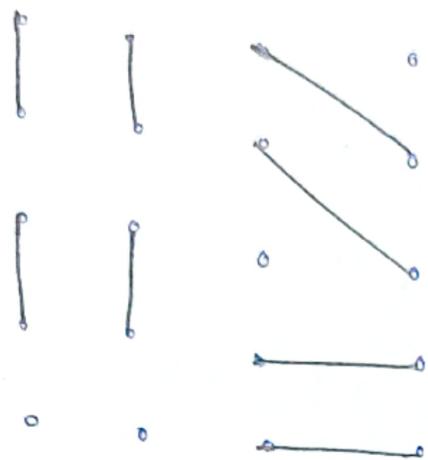
(a) 158 pm

(b) 74 pm

(c) 142 pm

(d) 126 pm

Crystal Planes :- when lattice point joined together in crystal lattice in different directions, these are known as crystal planes.



Miller Indices: The crystal lattice consists of many parallel planes, it is difficult to write their geometric equations.

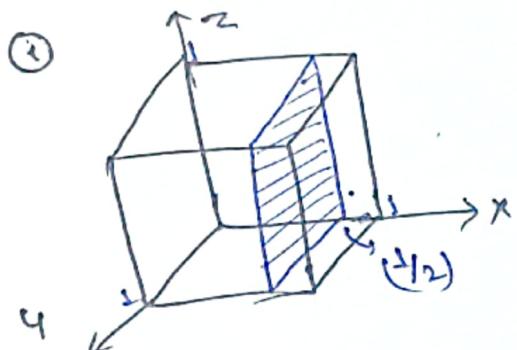
Miller evolved a method to designate a plane in a crystal by three numbers ( $hkl$ ).

⇒ Miller indices of a plane is defined as the reciprocal of intercept which the plane make with the axis when reduced to the smallest number.

⇒ He used the following steps to find Miller indices of a plane :-

- ① Determine the intercept of plane along three coordinate axis.
- ② Secondly, take the reciprocal of slope intercepts.
- ③ Taking whole number of the reciprocal by multiplying with their LCM.
- ④ Write the integer in a bracket to get Miller indices.

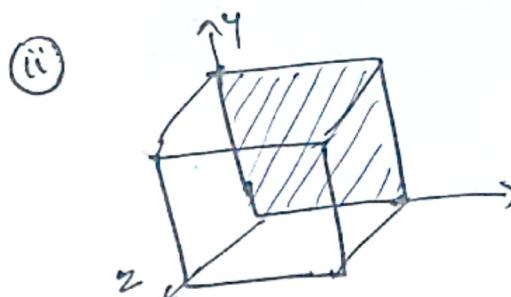
Ans: Get the miller indices of plane.



$$\text{intercept} = \left(\frac{1}{2}, 1, 1, \frac{1}{2}\right)$$

$$\therefore \text{reciprocal} = (2, 0, 0)$$

$$\therefore \text{Miller indices} = (1, 0, 0)$$



$$\text{intercept} = (\infty, \infty, 0)$$

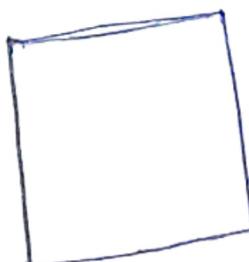
$$\text{reciprocal} = (0, 0, 1)$$

$$\therefore \text{m.i.} = (0, 0, 1)$$

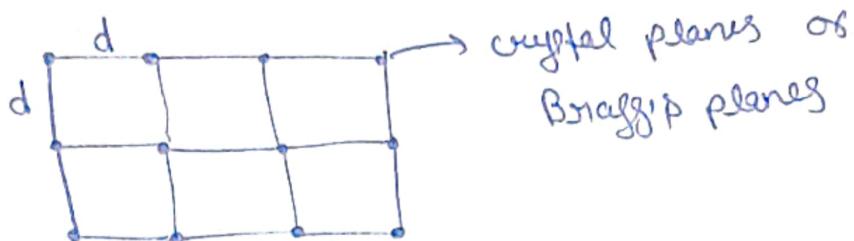
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pe kahte hoga  
mi I so

Ans: Draw plane for miller indices (1, 0, 0). don't use comma  
(negative axis lieg) use bar.

i (100)



Interplanar Distance (d): The separation b/w two successive planes is known as interplanar distance 'd'.



Relation b/w 'd' - edge length and interplanar distance 'd':

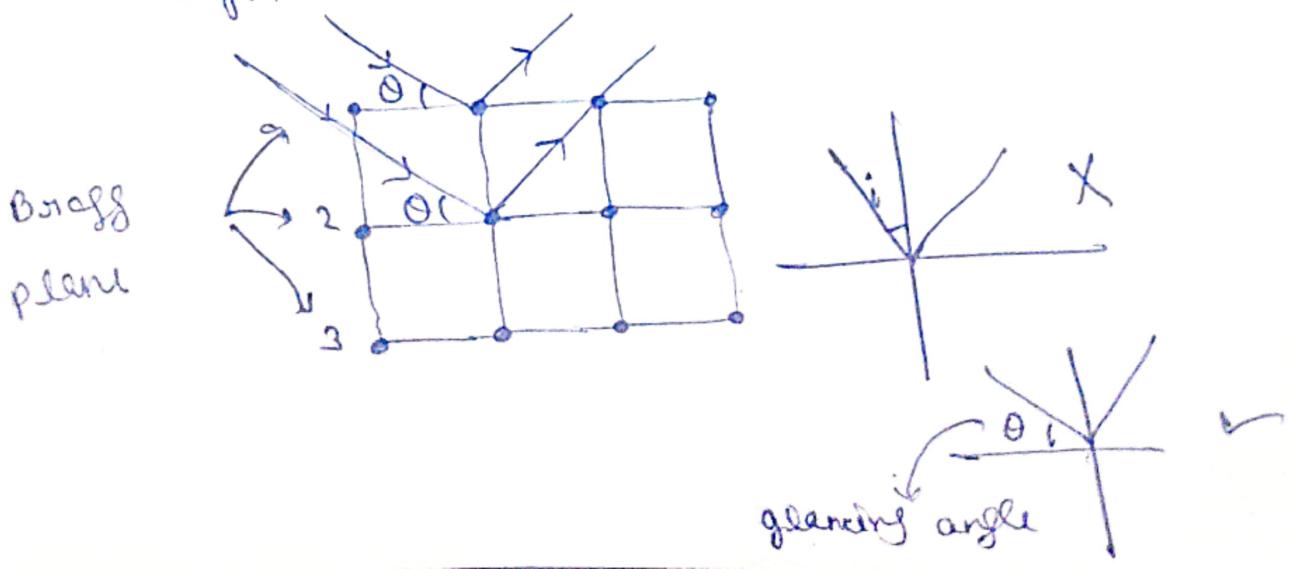
$$d = \frac{a}{\sqrt{h^2 + k^2 + l^2}}$$

where  $hkl$  are Miller indices.

In general

$$d = \frac{1}{\sqrt{\frac{h^2}{a^2} + \frac{k^2}{b^2} + \frac{l^2}{c^2}}}$$

Glancing angle: The angle of incidence ' $\theta$ ' is measured by Bragg's plane in a crystal is known as glancing angle ' $\theta$ '



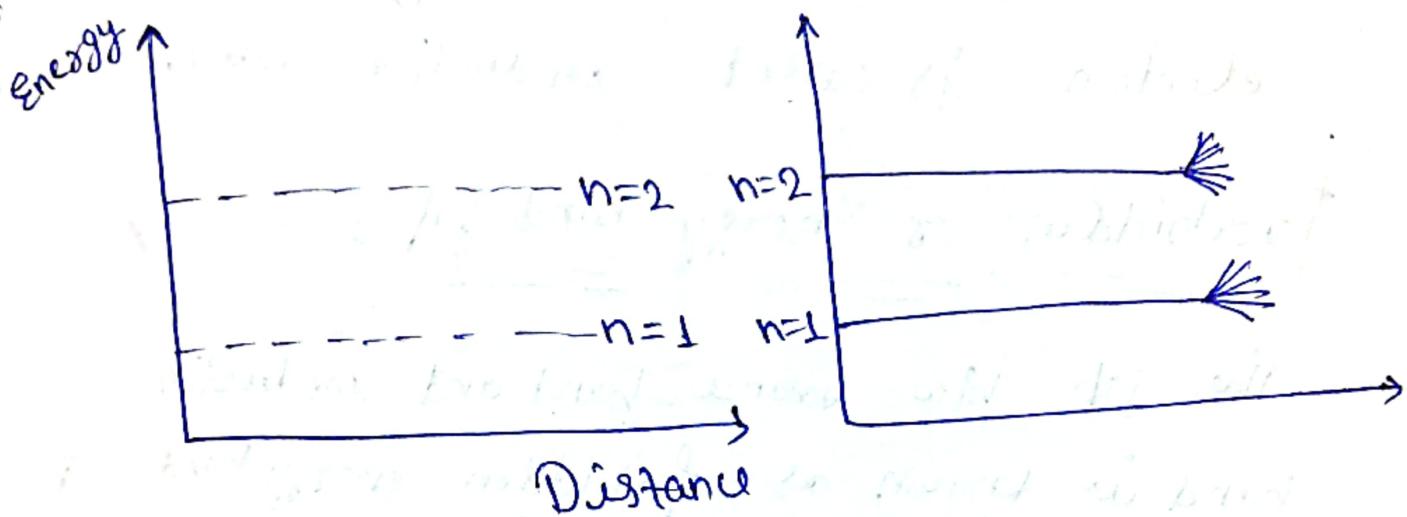
## Bragg's law : (Crystal Study - X-ray)

To understand the Bragg's law consider a parallel beam of x-ray is incident on the crystal lattice at atom A and B then the light is reflected from atoms A and B. both reflected rays are coherent, interfere with each other, as a result we get constructive interference depending on their path difference.

## Unit : 2

### Semi-Conductor Physics

#### Band Theory in Solids



In a solid, atoms are very close to each other, therefore the interaction b/w the electron of different atom in the same orbit takes place. as a result, the energy of electron in the same orbit get modified and forms a band known as energy band.

⇒ Hence, the range of energies possessed by the electron in the same orbit in a solid known as energy band.

Valence band: The range of energies possessed by the valence electrons or outermost shell electrons is called Valence band.

Conduction band: The range of energies possessed by free electron is called conduction band.

forbidden or Energy band gap:

The gap b/w valence band and conduction band is known as forbidden energy band gap.

⇒ The unit of band is eV or Joule.

for ex: Silicon have 1.1eV band gap,  
germanium have 0.7eV band gap

Classification of conductors, Insulators and Semiconductors on the basis of band theory:

According to band theory:

⇒ Solids are divided into three categories:

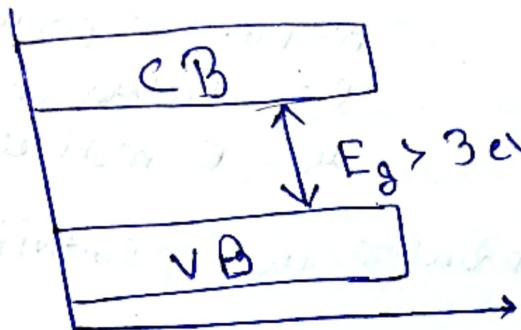
i) Insulator

ii) Conductor

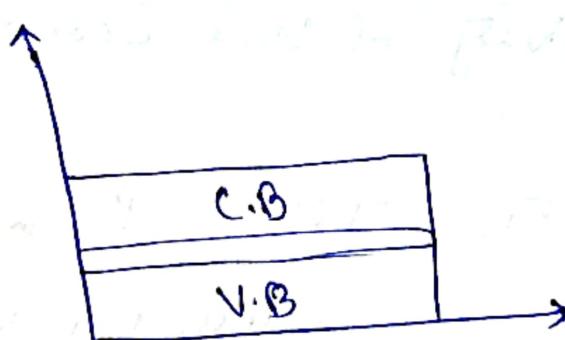
iii) Semi-conductor

Insulator: In insulator, the valence band is completely full & while conduction band is empty.

they have large energy gap between valence band & conduction band (more than 3 eV)



Conductor: Conductors are the material in which conduction band and valence band overlap with each other.



Semi-conductor: The valence band & conduction band are separated by a small distance (1.1 eV for silicon and 0.7 eV for germanium).

⇒ Semiconductor behaves as insulator at temp. 0K.  
when temperature increases or small electric field is applied than  $e^-$  jump to the conduction band and conduct electricity.

Eg: Silicon, Germanium.

### Conductivity in Semiconductors:

According to free e- theory, the conductivity of metals are given by:

$$\sigma = n e \mu e \quad n = \text{no. of } e^- \text{ per unit volume}$$

$e = \text{electron charge}$   
 $\mu_e = e^- \text{ mobility.}$

In case of semiconductor, the conductivity due to  $e^-$  is  $\sigma_n = n e \mu_e$

similarly for holes  $\sigma_h = P e \mu_h$

where  $P$  is the no. of holes/volume;  $\mu_h$  is holesmobility

∴ the total conductivity of semi-conductor is given by

$$\begin{aligned} \sigma &= \sigma_n + \sigma_h = n e \mu_e + P e \mu_h \\ &= e (n \mu_e + P \mu_h) \end{aligned}$$

Intrinsic semiconductors are pure semiconductors.

Eg: Silicon, Germanium.

In intrinsic semiconductor,  
no. of holes = no. of  $e^-$   
 $n = P$

therefore the conductivity of intrinsic semiconductor  
is given by.

$$\sigma_i = e[n\mu_e + P\mu_h]$$

$$\sigma_i = ne[\mu_e + \mu_h]$$

### Conductivity in extrinsic Semiconductor

when a small amount of impurity atom is added to pure semiconductor than the semiconductor is called Extrinsic semiconductor.

they are of two types :-

① P-type extrinsic semiconductor

② N-type extrinsic semiconductor

### P-type Semiconductor

when trivalent impurity atom is added to pure semiconductor, than the semiconductor is called P-type semiconductors.

### Conductivity in P-type Semiconductor

In P-type semiconductor, the no. of holes or concentration of holes is much greater than concentration of  $e^-$ .

In P-type semiconductor, the holes concentration is represented by by  $N_A$  (where  $N_A$  is the concentration of acceptor atom).  
therefore the conductivity for P-type Semiconductor  
is  $\sigma_h = e N_A \mu_h$

$$\boxed{\begin{aligned}\sigma_h &= e N_A \mu_h \\ \sigma_n &= e N_D \mu_n\end{aligned}}$$

### N-type Semiconductor

N-type semiconductors are those semiconductors which is produced when pentavalent impurity is added to intrinsic semiconductor.

→ the majority charge carriers in of N-type semiconductor are  $e^-$ .

④ the conc. of  $e^-$  also represented by  $N_D$  (conc. of donor atom)

and  $\sigma_p = n e \mu_e$

$$\boxed{\sigma = N_D e \mu_e}$$

## Fermi - Dirac Probability Distribution fn

Fermi - Dirac Probability Distribution fn, gives the probability of finding the electrons in particular energy level of energy E at particular temperature T.

The Fermi - Dirac Probability distribution fn is given by

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

where  $E \rightarrow$  energy of  $e^-$  of <sup>energy</sup> level having energy E

$E_F \rightarrow$  Fermi energy

$k \rightarrow$  Boltzmann constant

$T \rightarrow$  absolute temperature (in K).

To study the Fermi - Dirac probability fn for the following cases :-

i)

when  $E < E_f$  and  $T = 0K$

$\therefore E - E_f$  is -ve



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

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

$$F(E) = 1$$

ii)

when  $E > E_f$  and  $T = 0K$

$\therefore E - E_f > 0$



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

$$F(E) = 0$$

- ④ Case i) & case ii) concluded that all energy levels are occupied at 0K when  $E < E_f$  and empty when  $E > E_f$ .

Fermi-level:

It is the energy in a solid below which all energy levels are occupied and ~~empty~~ all energy levels above this are empty at 0K.

(\*) In another words, Fermi energy is maximum energy occupied by  $e^-$  at 0K.

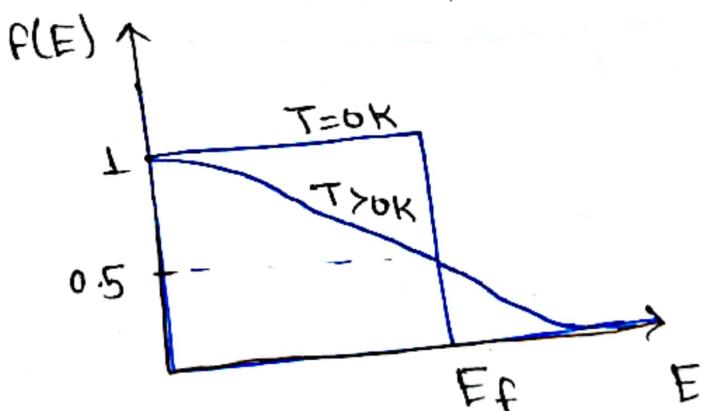
(iii) If  $E = E_F$  and  $T > 0K$

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

$$F(E) = \frac{1}{1+1} = \frac{1}{2}$$

\* It concluded that, Fermi level may also be defined as that energy for which, the probability of occupation finding of electron is half at  $E = E_F$  at 0K.

→ The variation of  $F(E)$  vs  $E$  at 0K and at  $T > 0$



Ques: find the value of  $F(E)$  for  $E - E_F = 0.01\text{ eV}$  at 200K

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

$$F(E) = \frac{1}{1 + e^{\frac{0.01}{8.6 \times 10^{-5} \times 200}}}$$

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

Ques: At what temp. can we expect a 10% probability that  $e^-$  in a metal will have an energy which is 5% above  $E_F$ . The Fermi energy of metal is 5.5 eV.

## Fermi-level :-

Fermi level is the energy level that corresponds to the center of gravity of  $e^-$  and holes weighted according to their energies.

## Fermi-level in intrinsic semiconductor :-

In intrinsic semiconductor,

no. of  $e^-$  & no. of holes are equal therefore, fermi level lie in the middle of conduction band and valence band.

## Semiconductor :-

no. of  $e^-$  & no. of holes

## Derivation :-

→ In intrinsic semiconductor, no. of  $e^-$  is given by :-

$$n = N_c e^{-(E_c - E_f)/kT}$$

$K$  = boltzmann constant

$T$  → absolute temp.

$E_c$  = lowest energy of conduction band

$E_f$  = fermi-level energy

$N_c$  = Density of state function in conduction band /

$k = 1.38 \times 10^{-23} \text{ J/K}$  / allowed energy states C.B.

$$1.38 \times 10^{-23}$$

→ No. of holes in valence band :-

$$P = N_v e^{-(E_f - E_v)/kT}$$

$N_v$  = density of state fn in V.B.

$E_v$  = highest energy of N.B.

$m_e^*$  = effective mass of  $e^-$ .

$$N_c = \left( \frac{2\pi m_e^* k T}{h^2} \right)^{3/2}$$

$$N_V = \left( \frac{2\pi m_n^* kT}{h^2} \right)^{3/2}$$



In intrinsic semiconductor,

no. of  $e^-$  = no. of holes

$$N_c e^{-(E_C - E_F)/kT} = N_V e^{-(E_F - E_V)/kT}$$

$$\frac{N_c}{N_V} = \frac{e^{-(E_F - E_V)/kT}}{e^{-(E_C - E_F)/kT}}$$

$$\frac{N_c}{N_V} = e^{(E_C + E_V - 2E_F)/kT}$$

$$\log\left(\frac{N_c}{N_V}\right) = \frac{E_C + E_V - 2E_F}{kT}$$

in intrinsic semiconductor,  $N_c = N_V$

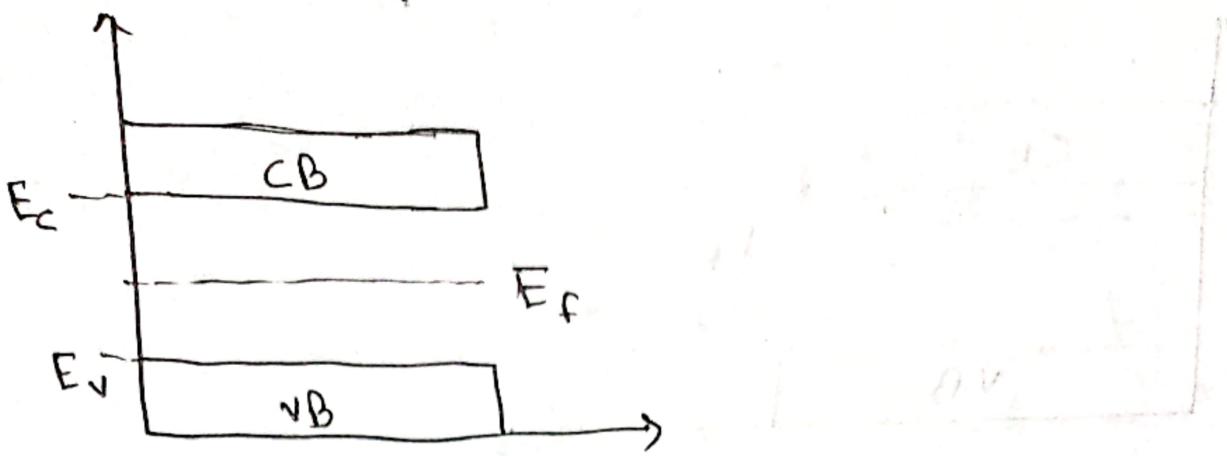
$$\log(1) = \frac{E_C + E_V - 2E_F}{kT}$$

$$E_C + E_V = 2E_F$$



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

→ which shows that, fermi level lies between C.B. & V.B. in intrinsic semiconductor.



Fermi level in N-type Semiconductor:

In N-type semiconductor,  $e^-$  are the majority charge carriers. Now fermi level is upward direction and shifted towards the conduction band.

In N-type semiconductor,

No. of  $e^-$  = No. of donor atoms,

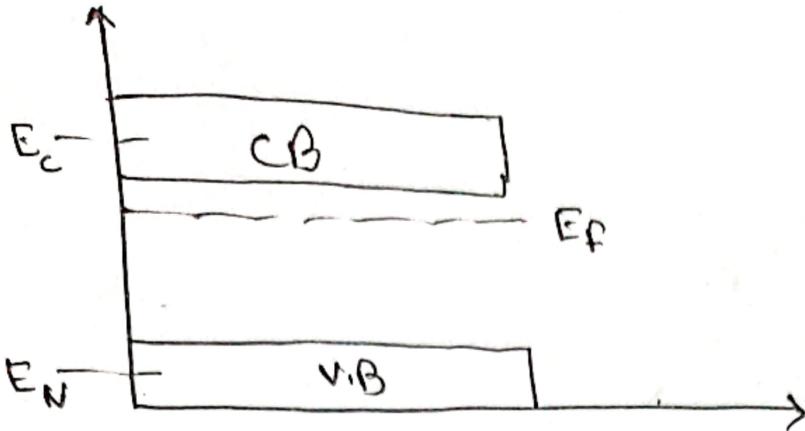
$$n = N_D$$

$$N_c e^{-(E_C - E_F)/kT} = N_D$$

$$\frac{N_c}{N_D} = e^{(E_C - E_F)/kT}$$

$$\log \left( \frac{N_c}{N_D} \right) = (E_C - E_F)/kT$$

$$E_F = E_C - kT \log \left( \frac{N_c}{N_D} \right)$$



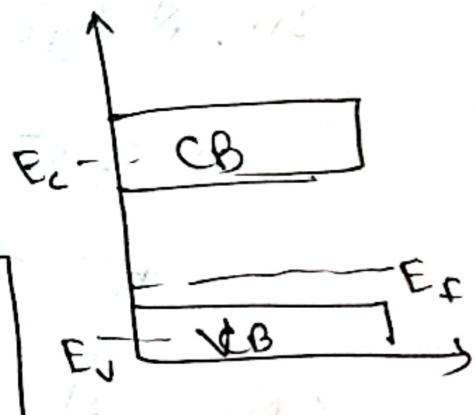
Fermi level of p type semiconductor

$$P = N_A \rightarrow \text{no. of acceptor atom}$$

$$N_V e^{-(E_F - E_V)/kT} = N_A$$

$$\times \frac{N_V}{N_A} = e^{(E_F - E_V)/kT}$$

$$E_F = E_V + kT \log \left( \frac{N_V}{N_A} \right)$$



Free charge carriers density in

intrinsic semiconductor

In intrinsic semiconductor, carrier density is represented by

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

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

$$n_i^2 = N_c e^{-(E_C - E_F)/kT} \cdot N_V e^{-(E_F - E_V)/kT}$$

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

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

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

Ans<sup>n</sup> In a P-type semiconductor, the fermi-level is 0.3 eV above the valence band at temp. 300K. determine the new position of fermi-level at temp. 400K.

Sol<sup>n</sup> as  $E_F = E_V + kT \log \left( \frac{N_V}{N_A} \right)$

$$E_F = E_V + 0.3$$

$$E_F - E_V = 0.3 \quad \text{--- (1)} \quad \text{at temp } 300K$$

as  $E_F - E_V = kT \log \left( \frac{N_V}{N_A} \right)$

$$0.3 = k(300) \log \left( \frac{N_V}{N_A} \right) \quad \text{--- (2)}$$

Similarly  $E_F - E_V = K(400) \log\left(\frac{N_V}{N_A}\right)$  — (11)

on (10)/(11),

$$\frac{0.3}{E_F - E_V} = \frac{300}{400}$$

$$E_F - E_V = 0.4 \text{ eV}$$

~~degree~~ In an N-type semiconductor is 0.3 eV below the conduction band at 300K. if the temperature is increased and become 330K.

Sol:

$$E_F = E_C - KT \log\left(\frac{N_C}{N_D}\right)$$

$$E_F - E_C = 0.3 \text{ eV}$$

or at 300K

$$E_F - E_C = K(300) \log\left(\frac{N_C}{N_D}\right)$$

~~and~~  $\Rightarrow 0.3 \text{ eV} = K(300) \log\left(\frac{N_C}{N_D}\right)$

and at 330K,

$$E_F - E_C = K(330) \log\left(\frac{N_C}{N_D}\right)$$
 — (11)

on (10)/(11)

$$\frac{0.3}{E_F - E_C} = \frac{300}{330}$$

$$E_f - E_c = 0.33 \text{ eV}$$

## Bipolar Junction Transistor (BJT)

Transistor is a three terminal semiconductor device which can be used as amplifier and switch in electronics.

In transistor, there are two P-N junction,

one is emitter-base junction and another is base-collector junction.

These are three parts of transistor :-

- ① Emitter (E) :- Emitter is represented by E which is in medium size and supply  $e^-$  therefore it is heavily doped.
- ② Base (B) :- It is very thin and slightly doped, control transistor action
- ③ Collector (C) :- It is moderately doped & collects  $e^-$ .

## Types of Transistors:

There are two type of bipolar junction transistors,

- (i) PNP transistors
- (ii) NPN transistors

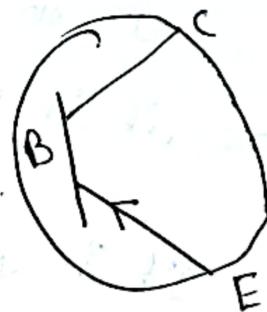
PNP Transistor: when N-type semiconductor is

sandwiched b/w two P-type

semiconductor, then BJT is known as PNP transistor.

In PNP transistor, emitter is of P-type semiconductor, base is N-type semiconductor, and collector is P-type semiconductor.

⇒ the notation of P-NP transistor is shown in diagram

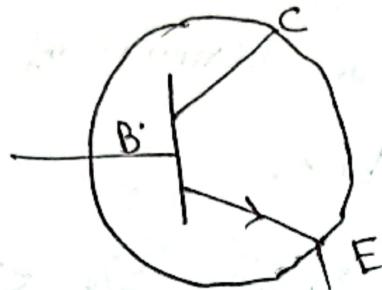


NPN Transistor: when a P-type semiconductor

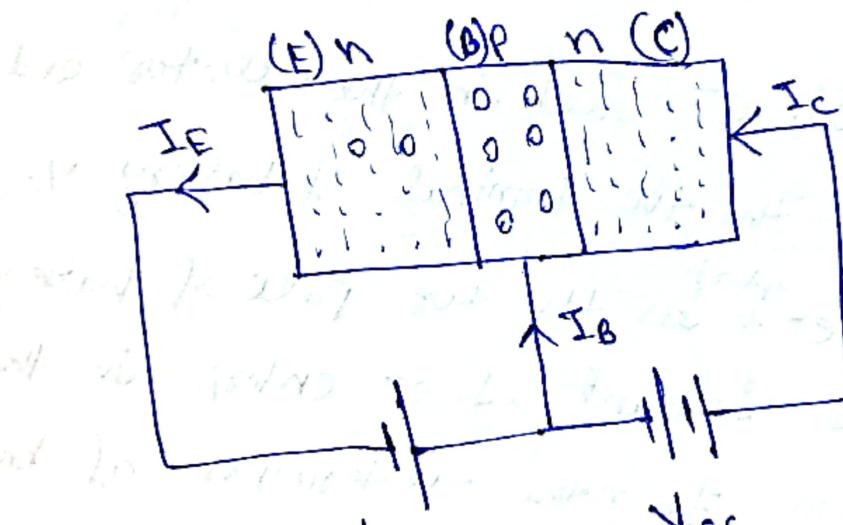
is sandwiched b/w two N-type semiconductor than BJT is called NPN transistor.

In NPN transistor, emitter is N-type semiconductor, base is P-type semiconductor and N collector is N-type semiconductor.

⇒ In NPN transistor, the notation shown below



### Working of NPN transistor



$$I_E - I_B - I_C = 0$$

$$I_E = I_B + I_C$$

⇒ The working of NPN transistor is shown in diagram. Ans / Different

- ④ In diagram, N-type emitter is connected to the -ve terminal of battery  $V_{EE}$ . therefore, emitter-base junction is forward biased.

- (\*) Similarly, N-type collector is connected by the +ve of the battery  $V_{cc}$ . therefore, collector-base junction is reverse biased.
  - (\*) The majority charge carriers in the emitter are repelled due to the -ve terminal of battery  $V_{EE}$  and move towards the base.
  - (\*) Base is very thin. So only 5%  $e^-$  are recombine with the holes in the base region which constitutes the base current  $I_B$ .
  - (\*) Rest of 95%  $e^-$  reach in the collector and attracted by the +ve terminal of battery  $V_{cc}$ .
  - (\*) When an  $e^-$  enters in the +ve pole of battery  $V_{cc}$  at the same instant, 1  $e^-$  enters in the emitter region from the -ve terminal of battery  $V_{cc}$ . As a result emitter current  $I_E$  and collector current  $I_C$  also flow in the circuit which is shown in diagram.
- The emitter current  $I_E$  is given by,

$$I_E = I_B + I_C$$

# Working Principle of PNP Transistor:

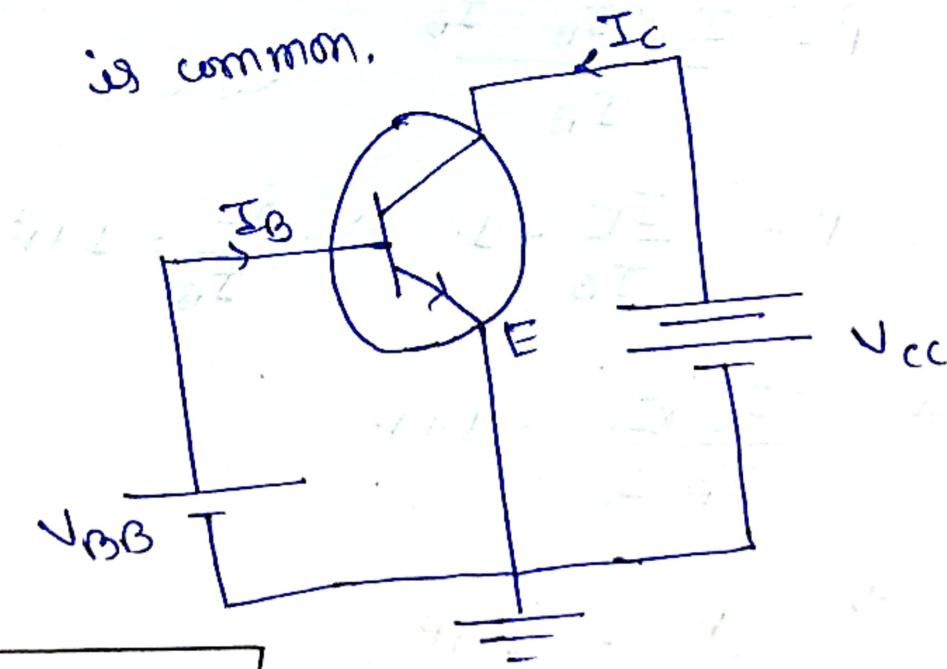
## Configuration of N-P-N transistor:

There are three type of configuration:

- ① Common - emitter
- ② Common - Base
- ③ Common - Collector

### ① Common-emitter configuration:

In common-emitter configuration, base is input terminal, collector is output terminal and emitter is common.

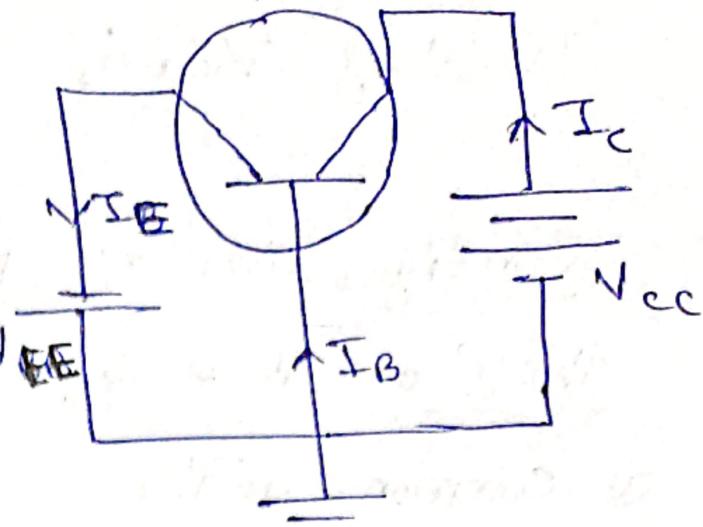


$$\beta = \frac{I_C}{I_B} > 1$$

(which is greater than 1)

## Common-Emitter Base configuration

In common base configuration,  
emitter is input terminal  
collector is output terminal  
and base is common.



$$\alpha = \frac{I_c}{I_E} < 1 \quad (\text{less than one})$$

## Relation b/w $\alpha$ & $\beta$

$$\alpha = \frac{I_c}{I_E}, \beta = \frac{I_c}{I_B} \quad \& \quad I_E = I_B + I_c$$

$$\beta = \frac{I_c + I_B - I_B}{I_B}$$

$$\beta = \frac{I_E}{I_B} - 1 \Rightarrow \frac{I_E}{I_B} = 1 + \beta$$

$$\Rightarrow \frac{I_c \times I_E}{I_B I_c} = 1 + \beta$$

$$\Rightarrow \frac{\beta}{\alpha} = 1 + \beta$$

~~$$\alpha = \frac{1 + \beta}{\beta}$$~~

$$\alpha = \frac{\beta}{1 + \beta}$$

### Common Collector Configuration

Output voltage is not affected by adjustment.

Output current is zero.

Output resistance is high.

Input resistance is low.

$$r = \frac{I_E}{I_B}$$

Ques: Calculate the  $\beta_E$  for  $I_B = 2\text{mA}$  and  $\beta = 100$

Sol:  $I_B = 2\text{mA}, \beta = 100$

$$\beta = \frac{I_C}{I_B} \Rightarrow 100 = \frac{I_C}{2\text{mA}}$$

$$I_C = 200\mu\text{A}$$

$$\therefore I_E = I_B + I_C$$

$$I_E = (2 + 200)\mu\text{A} = 202\mu\text{A}$$

Ques:  $I_B = 100\mu\text{A}$  and  $R_C$  is  $3\text{mA}$ .

Calculate  $I_E, \beta, \alpha$ .

Sol:  $I_B = 100\mu\text{A}, I_C = 3\text{mA}$

$$I_E = 100\mu\text{A} + 3000\mu\text{A} = 3100\mu\text{A}$$

$$\beta = \frac{I_C}{I_B} = \frac{3000\mu\text{A}}{100\mu\text{A}} = 30$$

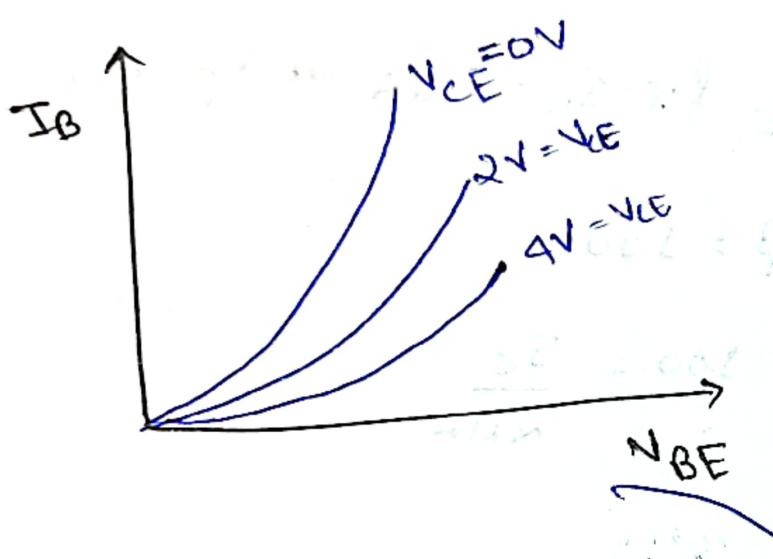
$$\text{and } \alpha = \frac{I_C}{I_E} = \frac{3000 \mu\text{A}}{3100 \mu\text{A}} = 0.97$$

## Characteristics of N-P-N transistor

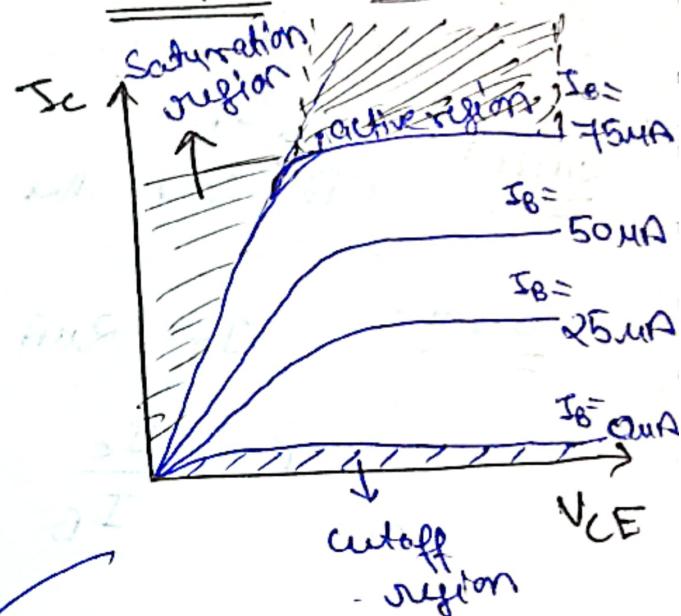
in CE configuration :-

~~(common collector, emitter)~~

### Input characteristics



### Output characteristics



### input characteristic :-

(see variation & need)

- (i) Input characteristics curve gives the relationship between  $I_B$  and  $V_{BE}$  at const  $V_{CE}$
- (ii) Beyond knee voltage base current increases in B-E voltage for silicon 0.7V and for Germanium 0.3V

5

## Output characteristics

Output characteristics gives the relation between  
 $I_C$  and

Solar cell

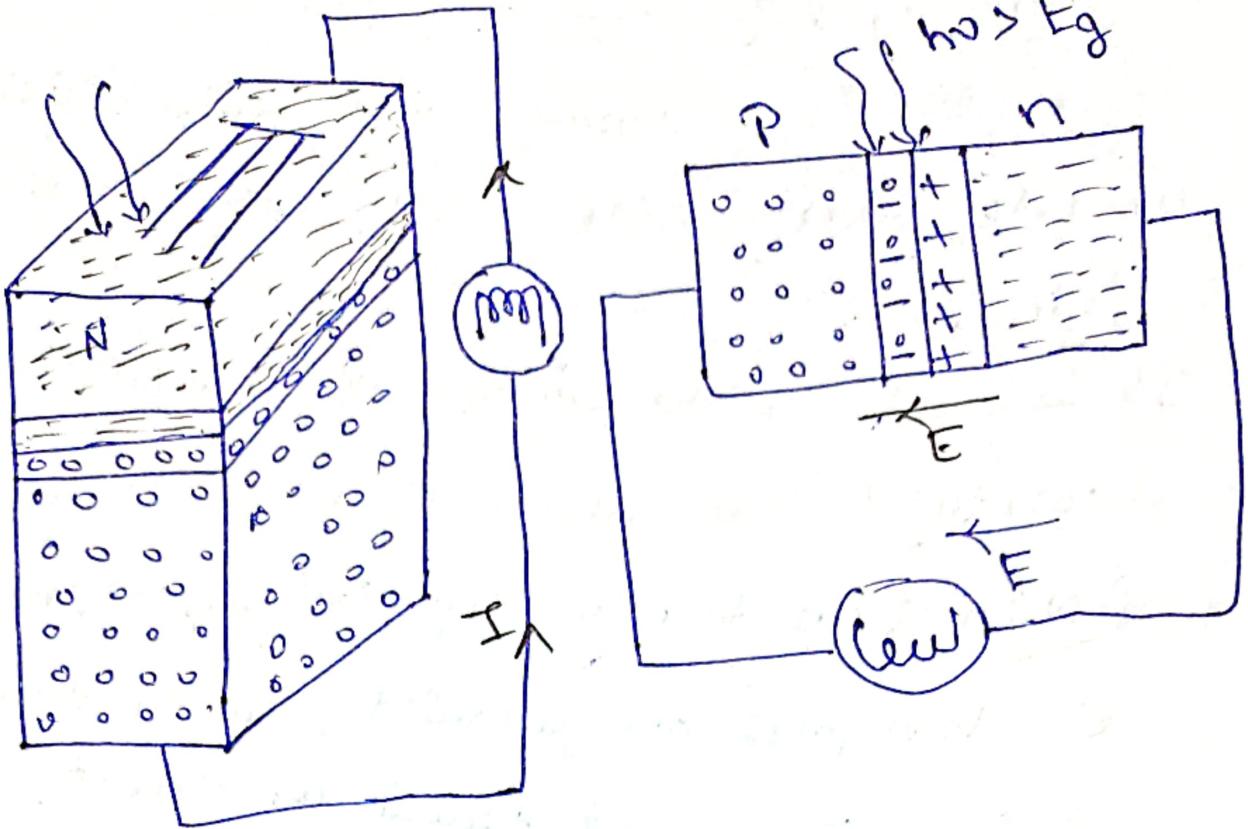
Solar cell is a semiconductive device which is used to convert solar energy into electrical energy.

### Principle:

It is based on the principle of photovoltaic effect. According to that when light is incident on P-N junction than in depletion region, more free  $e^-$ , hole pairs are generated, due to the movement of free  $e^-$  current flows in the circuit.

### Construction of Solar cell:

The construction of the solar cell is shown in diagram. It consists of a thin ( $0.3\text{ }\mu\text{m}$ ) N-type semiconductor and thick ( $300\text{ }\mu\text{m}$ ) P-type semiconductor, when they joined, they form P-N junction, near the junction a depletion region is created, metal fingers are deposited on the top N-region and another metallic layer on the bottom of P-region.



when a solar energy ( $h\nu > E_g$ ) is incident on the solar cell.

- i Due to the thin layer of N-region, light reached in the depletion region.
- ii As a result, more free  $e^-$ , hole-pairs are created.
- iii Due to the potential barrier,  $e^-$  move in the N-region and holes move towards the P-region.
- iv When intensity of light increases, more free  $e^-$ , hole-pairs are generated.
- v After some time  $e^-$  are collected in the N-region & holes are collected in P-region.

- ⑩ Metallic ligament provides less resistance path<sup>3</sup> of  $e^-$ .
- ⑪ Due to this,  $e^-$  flow from N-to P region in the circuit.
- ⑫ Therefore, current flow P-to N region in the circuit.
- ⑬ If load (like bulb) connected in the circuit then the bulb glow due to the flow of current

$\xrightarrow{\text{FF}}$  tells the measurement of how efficient a solar cell is.

Fill factor of a Solar cell %

$$FF = \frac{V_m \times I_m}{V_{oc} \times I_{sc}} = \frac{P_{output}}{V_{oc} \times I_{sc}} \quad \text{①}$$

then Efficiency of solar cell  
is given by,

$$\eta = \frac{P_{output}}{P_{input}} = \frac{V_m \times I_m}{P_{input}} = \frac{FF \times V_{oc} \times I_{sc}}{P_{input}}$$

$$\eta = \frac{FF \times V_{oc} \times I_{sc}}{\frac{\text{Solar energy}}{\text{area}} \times \text{area}}$$

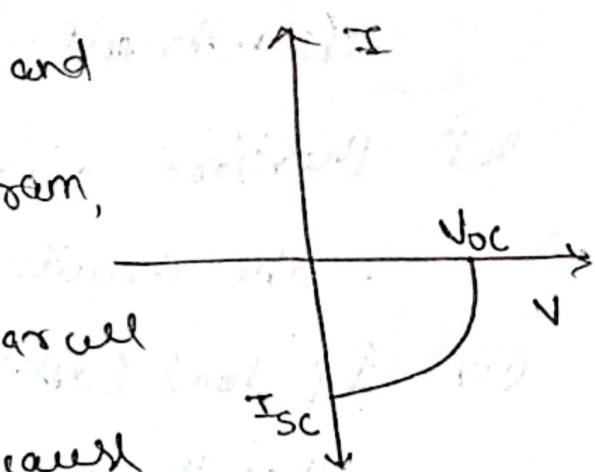
$\uparrow$   $\frac{\text{Solar energy}}{\text{area}} = \frac{P_{\text{Solar}}}{\text{area}}$  solar cell action

## Characteristics of Solar cell

The characteristics of a solar cell

is the variation b/w current and

voltage which is shown in diagram,



The V-I characteristic of solar cell

lies in the fourth quadrant because

solar cell supplied the current and

not taken.

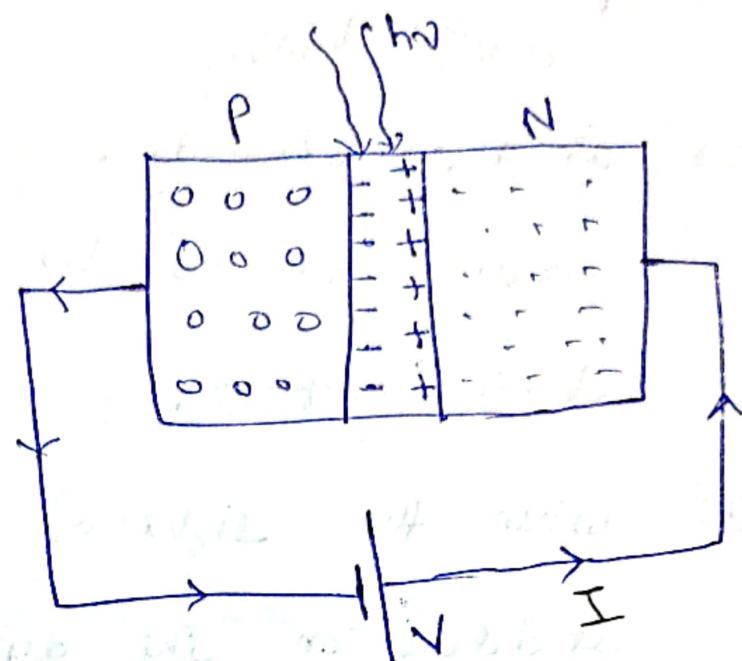
## Applications of Solar cell

- (i) Generation of solar power.
- (ii) Solar pump irrigation.
- (iii) Solar power vehicle.
- (iv) Street light
- (v) Solar water distillation.

# Photo Diode

It is a P-N junction semiconducting device which converts light energy to electrical energy, it is operated

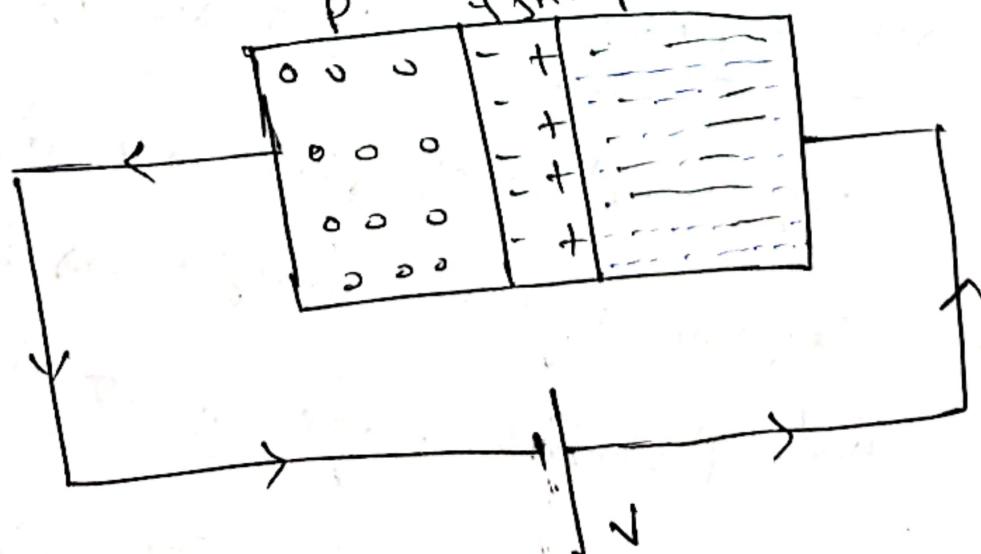
in reverse bias before breakdown voltage.



## Construction and Working

The construction and working diagram of

photodiode is show in figure.



diag. ①

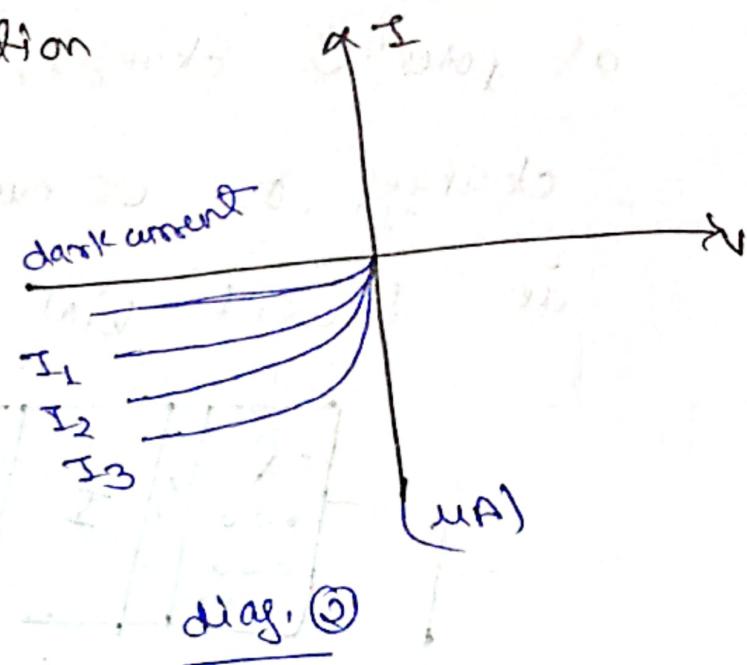
- ④ It consist P-N junction which is in reverse bias.
- ⑤ as a result dark current flow in the circuit due to the flow of minority charge carriers,
- ⑥ when the light of energy  $\hbar\nu > E_g$  is incident on the depletion region.
- ⑦ Additional  $e^-$ , hole-pairs are generated
- ⑧  $e^-$  moves towards the N-region and holes moves towards the P-region.
- ⑨ As a result dark current increased.

### Characteristics of Photodiode

- ① The characteristics of photodiode is shown in diagram ② when sunlight is incident on the photodiode, dark current increases.
- ② when the intensity of light increases, dark current also increases.

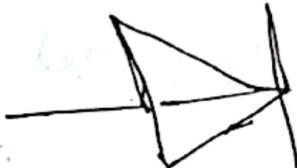
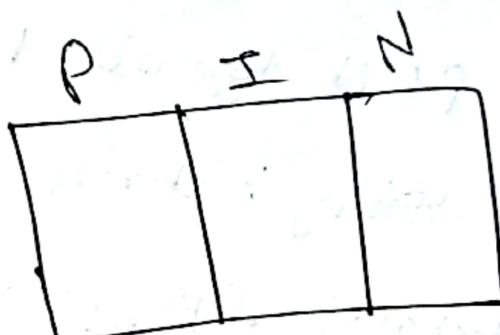
## Applications of Photo diode's

- ① for sensing application
- ② In counting machines
- ③ In optical fibres



## PIN Diode:

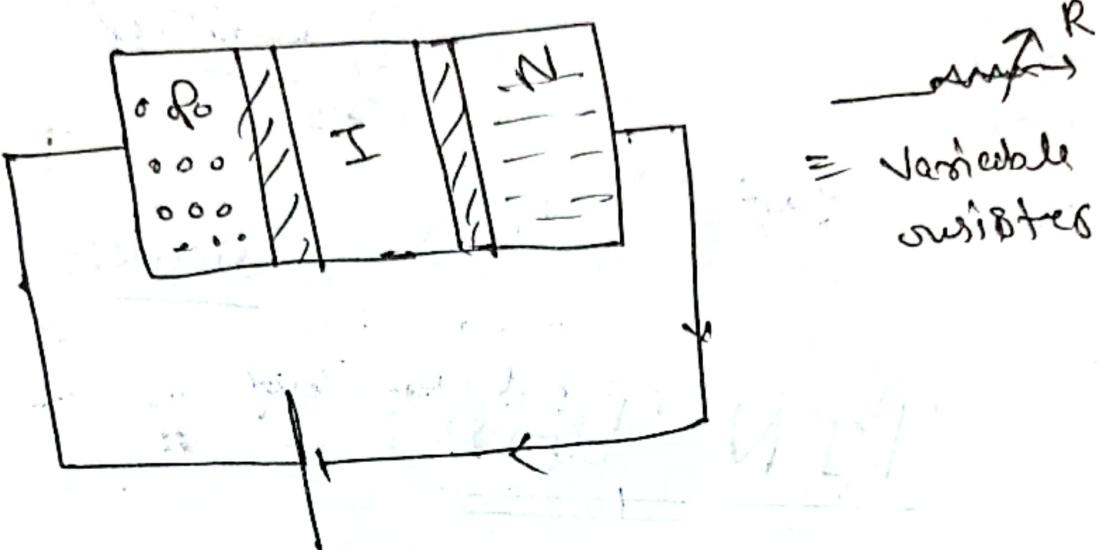
Between P-type and N-type semiconductor, Intrinsic semiconductor is placed called PIN Diode.



## PIN Diode in forward Bias:

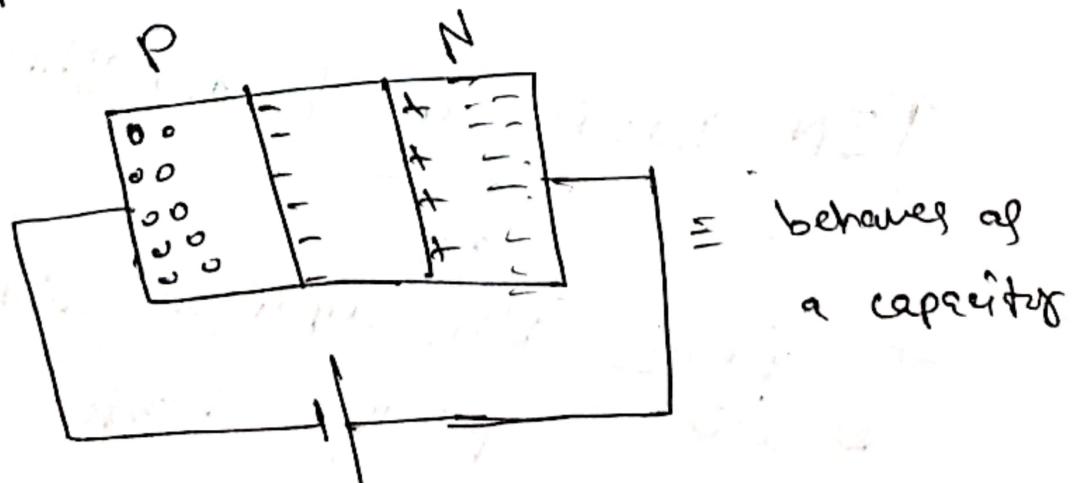
In forward bias, depletion width is small as well as potential barrier is small,

therefore current flow easily in the circuit, as potential changes, because of no potential changes, or we can say that P<sub>J</sub>N diode in forward bias act as variable resistor.



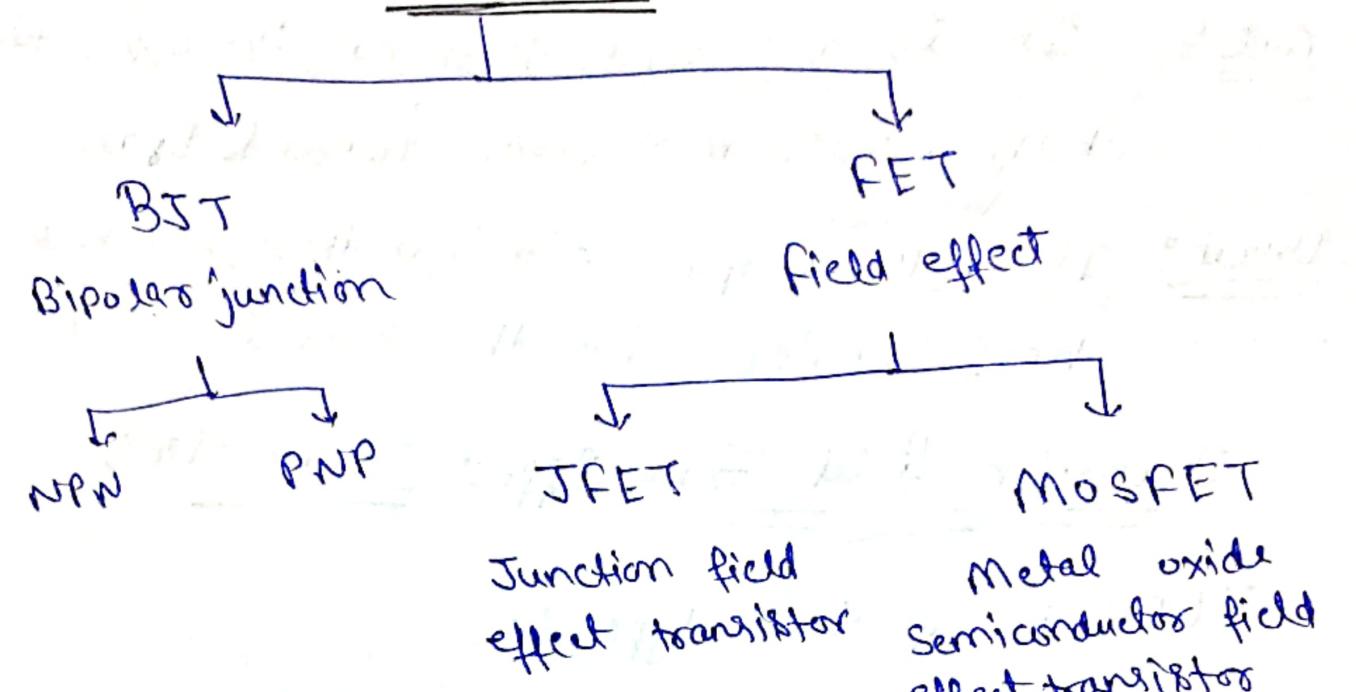
### PIN Diode in reverse bias?

In reverse bias, width of depletion region is increased, so P+N type will behave like two plates for storing charge. In this way P<sub>J</sub>N diode behaves like capacitor.



## Unit 2 (left portion)

### Transistor



### Field Effect Transistor

FET is a voltage controlled device in which output current depends on input voltage. It is also a unipolar device through which current flows due to either holes or electrons.

It is of two types :-

(i) JFET

(ii) MOSFET

It has three terminal,

(i) Source

(ii) Gate

(iii) Drain

Source: It is a first terminal through which charge carriers enter in the channel.

Gate: It is a second terminal through which charge carriers move from Source to Drain.

Drain: It is the output terminal through which charge carriers leave the channel.

### Junction field effect Transistor

JFET is of two types:

i) n-channel JFET

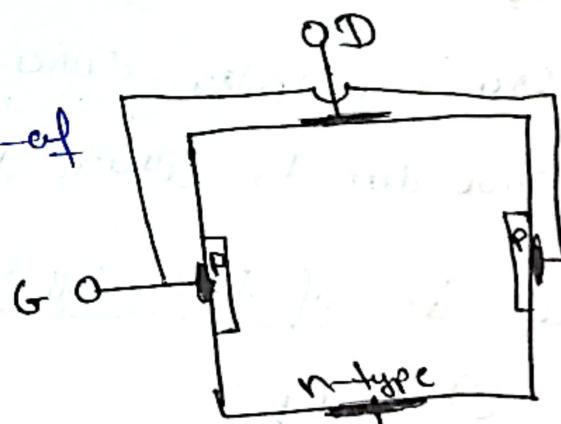
ii) p-channel JFET

#### i) n-channel JFET

i) n-channel JFET consist of

n-type semiconductor bar

called channel

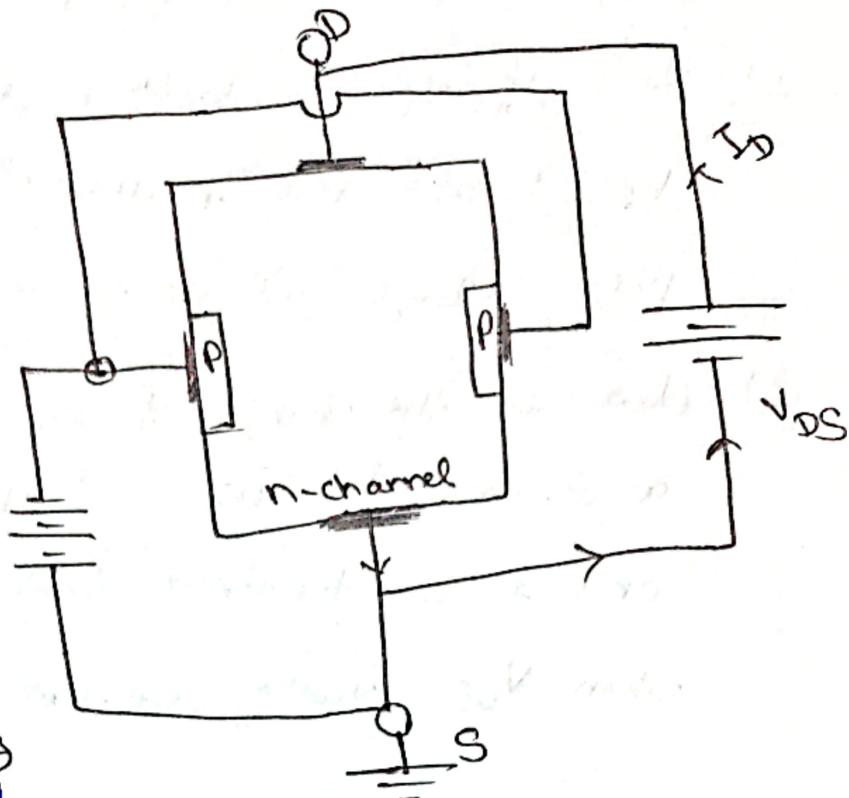
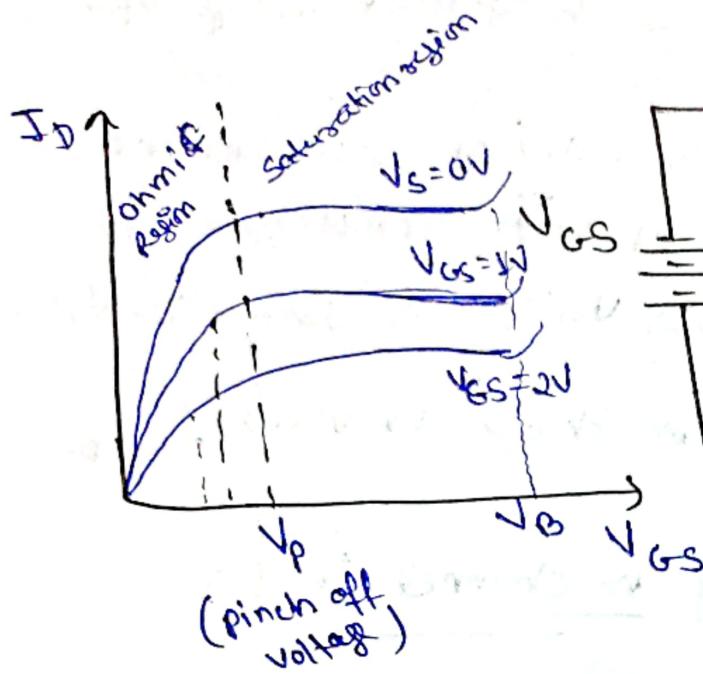


ii) Two p-type material are diffused on both sides of channel

which are internally connected via terminal called gate.

iii) On both sides of the channel, a conducting material are attached known as source & drain.

## Working



→ The circuit diagram of n-channel JFET is shown in figure

- ① When battery  $V_{DS}$  is applied across drain & source such that drain is at higher potential and source is at lower potential.
- ② Due to this e- flow from source to drain as a result drain current  $I_D$  flow from drain to source
- ③ When  $V_{GS}$  increases,  $I_D$  increases, and follow ohms law
- ④ At a particular value of  $V_{GS}$ ,  $I_D$  becomes saturated, this value of voltage  $V_{GS}$  is

Known as pinch off voltage  $V_p$ .

- ⑤ Now, if  $V_{DS}$  is further increases, at the covalent bond breaks and  $I_D$  increases rapidly. This voltage is known as breakdown voltage  $V_B$ .
- ⑥ Now, for the change of the value of drain current, a reverse biasing is applied across gate and source terminal, this voltage is denoted by  $V_{GS}$ . When  $V_{GS}$  varies, we can change the value of  $I_D$ .

### I-V characteristics of n-channel JFET

Relationship b/w  $I_D$  and  $V_{GS}$  for different different value of  $V_{DS}$  is shown in diagram which contains three region.

① Ohmic region

② Saturation region

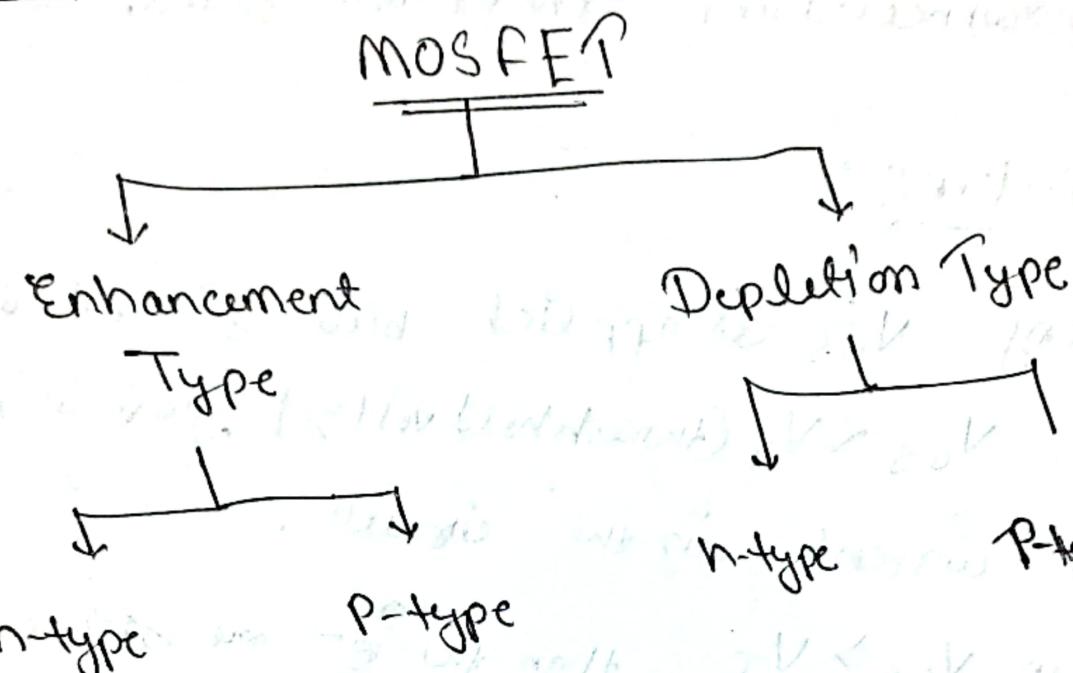
③ Breakdown

⇒ In ohmic region, when  $V_{GS}$  increases  $I_D$  increases.

⇒ In saturation region, at a particular voltage, called  $V_{GS} = V_p$ ,  $I_D$  become saturate. this region is called saturation region.

⇒ In the breakdown region,  $J_B$  increases rapidly. The value of  $V_{DS}$  is known as breakdown voltage  $V_B$ , which is shown in diagram.

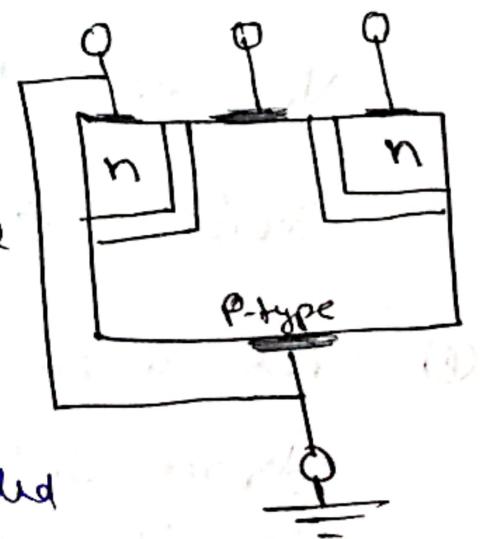
## Metal Oxide Semiconductor Field Effect Transistor



n-type  
Enhancement type  
MOSFET

### Construction:

- ① N-type enhancement MOSFET consist of P-type substrate in which 2 n-type well are embedded in the P-type substrate



- ② one n-type well is called source terminal, 2nd n-type well is called drain terminal

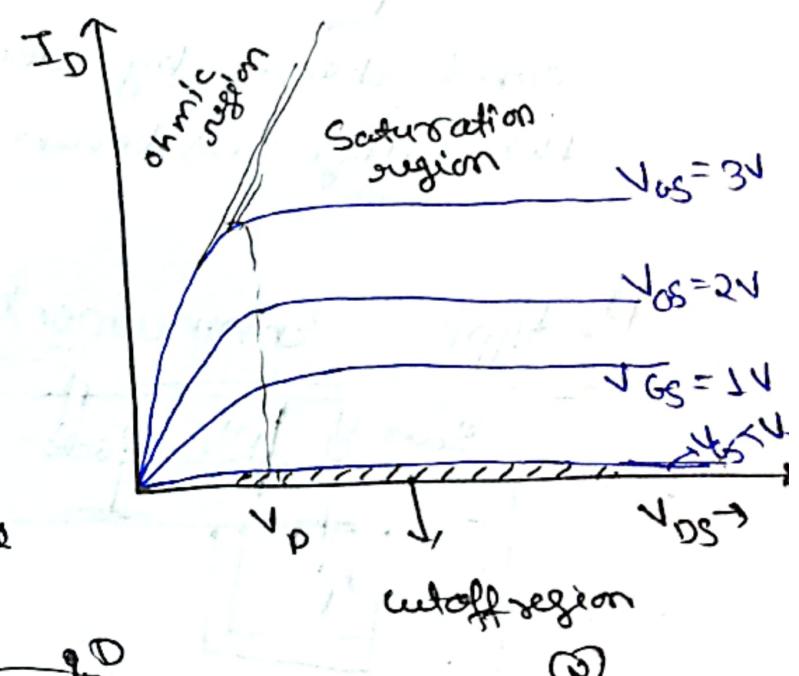
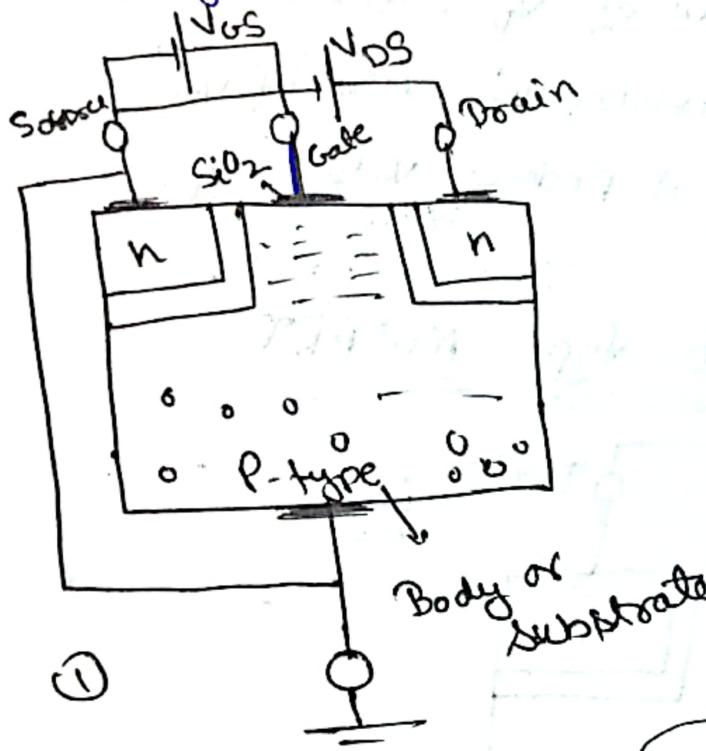
- ④ A thin  $\text{SiO}_2$  layer is also deposited b/w source and drain, this terminal is known as gate terminal.
- ⑤ Substrate terminal and source terminal are interconnected and connected with ground.

### Working :

- ① Battery  $V_{GS}$  is applied b/w gate and source when  $V_{GS} < V_T$  (threshold voltage), there is no drain current in the circuit.
- ② when  $V_{GS} > V_T$ , then more electrons are collected near the  $\text{SiO}_2$  layer, than this region behaves as n-type.
- ③ In order to flow, drain current ( $I_D$ ), a battery  $V_{DS}$  is connected b/w source and drain, which is shown in diagram, as a result, drain current  $I_D$  flows from drain to source terminal.
- ④ when  $V_{DS}$  increases,  $I_D$  increases according to ohm's law.

⑥ At a particular value of  $V_{DS}$ ,  $I_D$  becomes saturated, this value of  $V_{DS}$  is known as Pinch off Voltage  $V_p$ . In order to change the value of  $I_D$  we have to increase it.

⑦ In order to increase the value  $I_D$ , increase the value of  $V_{GS}$ , when  $V_{DS}$  increases,  $I_D$  increases by increasing  $V_{DS}$  and then saturates.



V-I characteristic of n-type enhancement MOSFET

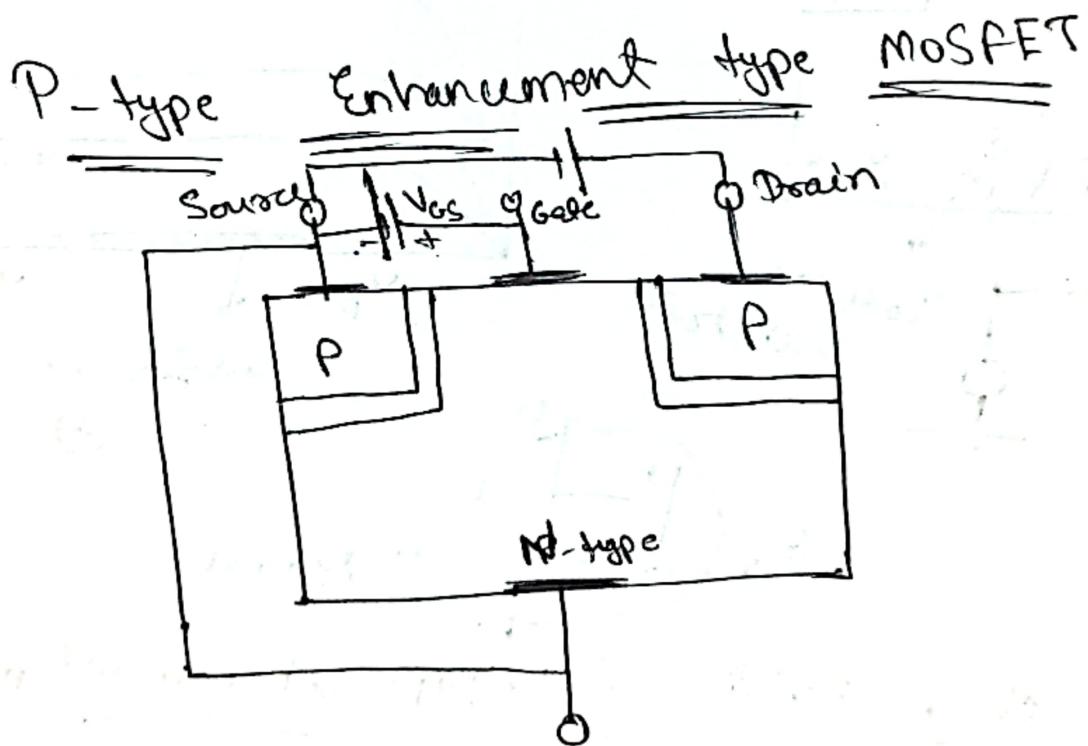
V-I characteristic is shown in diagram(2).

- ① Cutoff region
- ② Ohmic region
- ③ Saturation region

Cutoff region: when  $V_{GS} < V_T$ , there is no drain current, this region is called cutoff region.

Ohmic region: In ohmic region,  $I_D$  increases by increasing  $V_{DS}$ , this region is called ohmic region.

Saturation region: In saturation region,  $I_D$  is constant at a particular value of  $V_D$ . after that  $I_D$  can't change by increasing the value of  $V_{DS}$ . this voltage is known as pinch off voltage  $V_p$ .

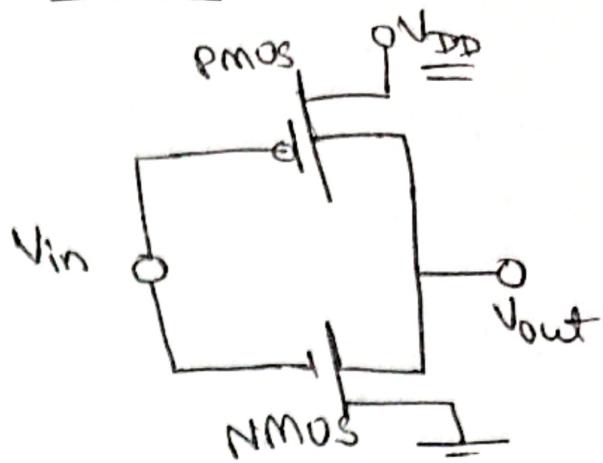


# CMOS

Complementary metal oxide semiconductor

Truth table:

<u>V<sub>in</sub></u>	<u>PMOS</u>	<u>NMOS</u>	<u>V<sub>out</sub></u>
1	0	1	0
0	1	0	1



The CMOS circuit uses both P-type and N-type transistors

Ques: Difference between BJT and FET.

Ans:

BJT

- ① It is bipolar
- ② Current controlled device
- ③ Consumes more power
- ④ uses both e-holes for conduction
- ⑤ used in analog circuits  
e.g. amplifiers.

FET

- ① It is unipolar
- ② Voltage controlled device
- ③ consumes less power
- ④ uses either e or holes for conduction.
- ⑤ used in digital circuits  
e.g. switches.

Sol ①  $\beta / k_T = 1.1 \text{ k}\Omega$

- $\Rightarrow$  ① BJT having 3 terminals , -  
② JFET having 3 terminals  
③ MOSFET having 3 terminal (excluding substrate terminal)  
and including threshold.

# Unit : 4

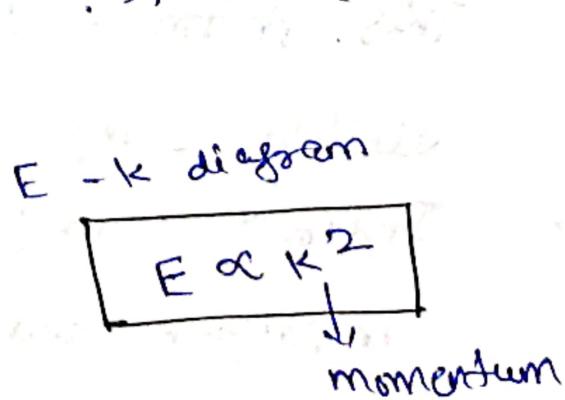
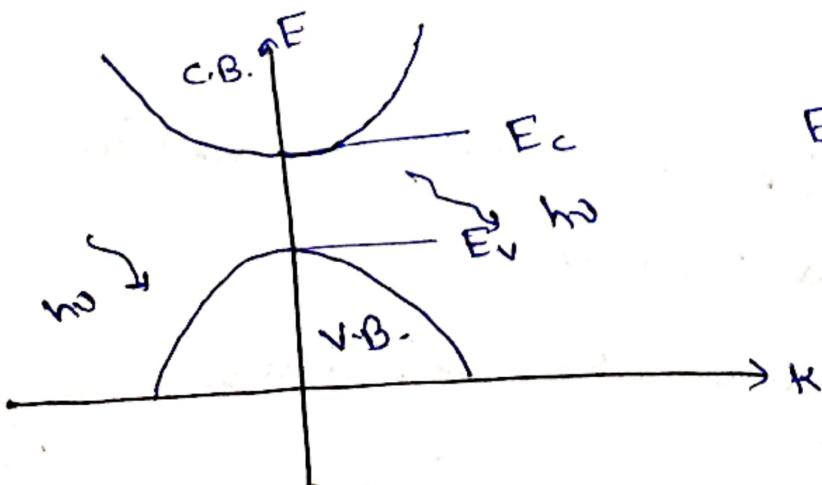
## Opto Electronic Devices

### Direct and Indirect Band Gap Semiconductors

#### Direct Band Gap Semiconductors

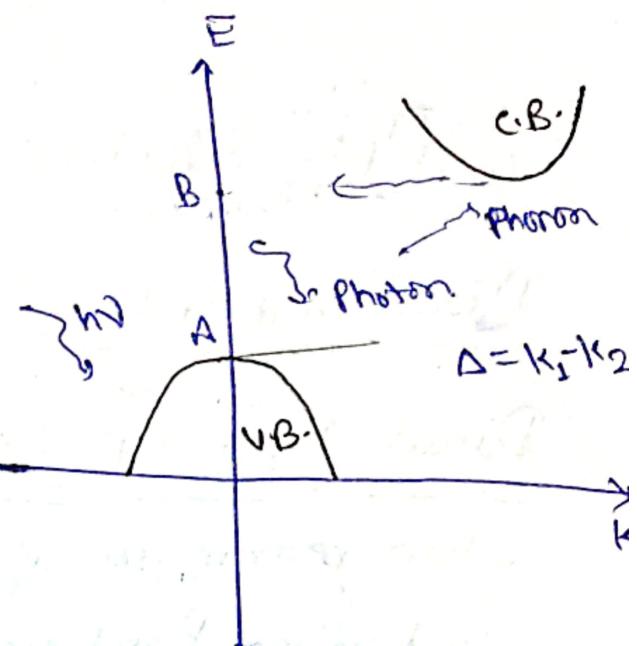
when maximum of valence band and minimum of conduction band occurs at same momentum then the semiconductor is called direct band gap semiconductor.

- (i) when an  $e^-$  is in valence band, absorbing energy  $h\nu$  goes to conduction band, then after some time  $e^-$  jump to valence band and emits a photon of energy  $h\nu$  which is equal to  $(E_c - E_v)$ .
- (ii) This light lies in the visible range.
- (iii) Direct band gap semiconductors are used in LEDs and laser diode.
- (iv) Examples : GaAs (Gallium Arsenide), InP (Indium Phosphide)



## Indirect Band Gap Semiconductors

when maximum of V.B. and minimum of conduction band occurs at two different values  $\hbar\omega$  of momentum known as Indirect Band Gap semiconductors.



- ⇒ when an  $e^-$  in V.B. after absorbing energy  $h\nu$  goes to conduction than  $e^-$  gain some energy from lattice vibration and moves to the bottom of the conduction band.
- ⇒ After some time, it come back to point B and emits Phonons. (Stay time  $\sim 10^{-8}$  sec)  
(only need)
- ⇒ Then  $e^-$  come back to valence band and emits photon.
- ⇒ This photon or light does not lie in visible range.
- ⇒ Indirect band-gap semiconductor are used in amplifiers and Transistors
- Eg: Indirect semiconductors like Si, Ge.

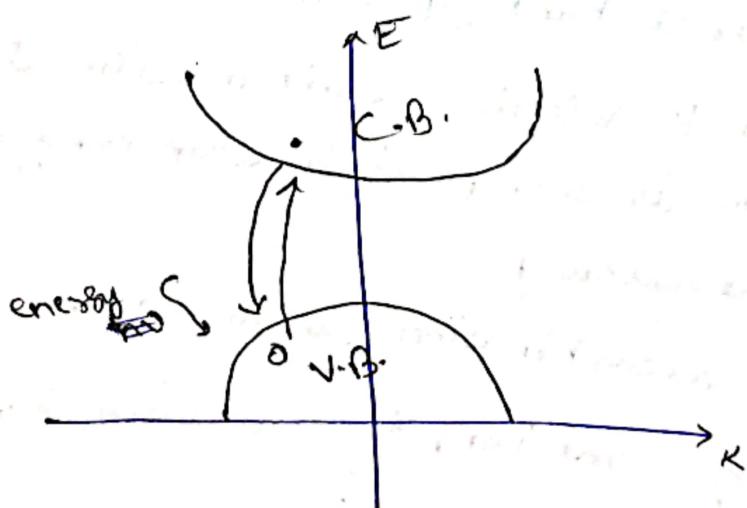
## Electron hole Pair Generation and Recombination:

### Generation of e<sup>-</sup>-hole pair:

- ⇒ when electrons in valence band get enough energy then they will absorb energy and jump to conduction band.
- ⇒ This e<sup>-</sup> in conduction band called thermally generated free e<sup>-</sup>.
- ⇒ The place where e<sup>-</sup> left is called hole.
- ⇒ Electrons and holes always generated in pairs.
- ⇒ The process in which thermally free e<sup>-</sup> and holes are generated in pairs is called generation of e<sup>-</sup>-hole pairs.

### Recombination of e<sup>-</sup>-hole pair:

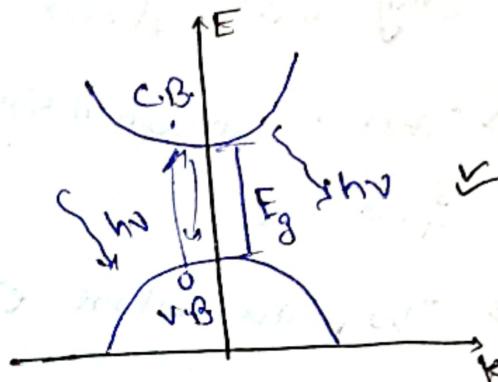
- ⇒ The process by falling back of thermally generated free e<sup>-</sup> to valence band and combine with hole is called e<sup>-</sup>-hole pair recombination.
- ⇒ when e<sup>-</sup> recombine with hole, it release energy.



## Radiative and Non-Radiative Recombination:

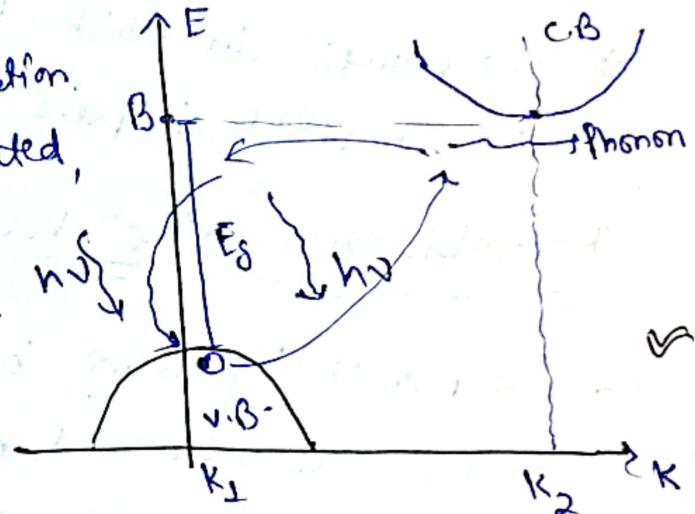
Radiative Recombination: In radiative recombination

process, the released energy is emitted as electromagnetic radiation.



Non-Radiative Recombination:

In a non-radiative recombination process, no radiation is emitted, and the released energy is eventually converted to thermal energy in the form of lattice vibrations.



Radiative Recombination:

(class)

- It occurs in direct band gap semiconductors.
- It follows the  $k$ -selection rule according to which emission is only possible when energy and momentum are conserved.
- In radiative recombination, when  $e^-$  valence band absorbs energy and jumps to conduction band and leave hole in valence band.

- ⇒ After some time, this thermally generated free  $e^-$  falling back in Valence band and recombine with hole.
- ⇒ In this process it radiate energy in the form of photon.
- ⇒ This photon lies in the visible range called Radiative Recombination. (figure same)

### Non-Radiative Recombination

- ⇒ It occurs in indirect band gap semiconductor.
- ⇒ In this process phonons are involved.
- ⇒ K-selection rule are not obeyed.
- ⇒ When an  $e^-$  in valence band after absorbing some energy goes to conduction band and leave hole in valence band.
- ⇒ Then  $e^-$  quickly moves to the bottom of conduction band by absorbing lattice vibrations called phonon.
- ⇒ After sometime it emits phonon and come at previous position in conduction band.
- ⇒ Now electron jump to the valence band and recombine with hole and release energy.
- ⇒ This energy or photon does not lie in the visible range called non-radiative recombination (figure same).

Ans: LED is constructed from Gallium Arsenide semiconductor material. The energy gap of this LED is 1.9 eV. Calculate the wavelength of light emitted.

Sol:  $E_g = h\nu = hc/\lambda$

$$1.9 \text{ eV} = \cancel{1.9 \text{ eV}} \quad hc/\lambda$$

$$\lambda = \frac{6.62 \times 10^{-34} \times 3 \times 10^8}{1.9 \times 1.6 \times 10^{-19}}$$

$$\boxed{\lambda = 6.53 \times 10^{-7} \text{ m}}$$

Ans: Calculate the energy of a photon in LED having wavelength  $6328 \text{ \AA}$ .

Sol:

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

$$(E)_p = \frac{6.626 \times 10^{-34} \times 3 \times 10^8}{6328 \times 10^{-10}}$$

$$(E)_{\text{photon}} = \frac{6.626 \times 3}{6328} \times 10^{-16} \times \left( \frac{1}{1.6 \times 10^{-19}} \right)$$

$$(E)_{\text{photon}} = 5.963 \text{ eV}$$

Ans: Calculate the energy band gap of GaAs having photo of wavelength  $6934 \text{ \AA}$ .

$$\underline{\text{Sol:}} \quad E = \frac{hc}{\lambda} = \frac{6.626 \times 10^{-34} \times 3 \times 10^8}{6334 \times 10^{-16}} \times \left( \frac{1}{1.6 \times 10^{-19}} \right) \text{ eV}$$

$$E = 1.78 \text{ eV}$$

Ques: The energy of CB and VB is 1.9eV and 1.8eV respectively. calculate wavelength.

$$\underline{\text{Sol:}} \quad \lambda = \frac{6.62 \times 10^{-34} \times 3 \times 10^8}{0.1 \times 1.6 \times 10^{-19}}$$

$$\lambda = hc/E$$

$$Eg = E_C - E_V \\ = 0.1 \text{ eV}$$

$$\lambda = 124.125 \times 10^{-7} \text{ m}$$

$$\lambda = 1.24125 \times 10^{-5} \text{ m or } 1.24125 \text{ Å}$$

## Homo - Junction LED, and Hetero Junction LED

### Homo-Junction LED

- ① If p-n junction is made up of same type of intrinsic atoms, then the LED is called Homo-Junction LED

- ② Layers have similar semiconductors but doping is different

- ③ It is also called surface emitting LED.

- ④ It is non-directional light.  
eg Si and GaAs solar cell, Ge.

### Hetero - Junction LEDs

- ① If p-n junction is made up of different intrinsic atoms then LED is called Hetero Junction LED.

- ② Layers have different semi-conductors i.e. having different energy band gap

- ③ It is also called edge emitting LED.

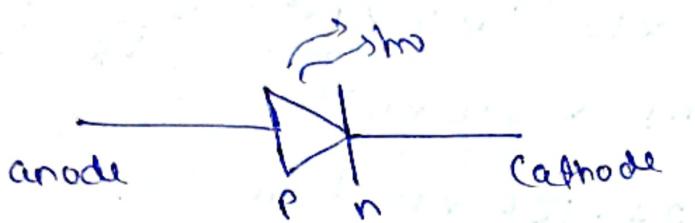
- ④ It is directional light.

- ⑤ Gallium Arsenide phosphide

## LED's

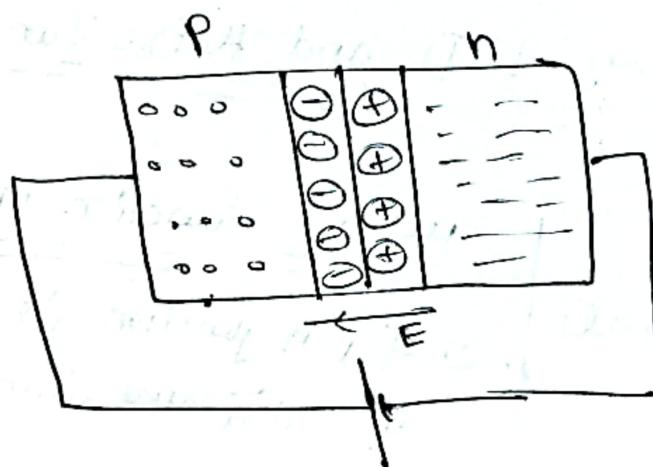
Light emitting diode which is used to emit light.

- ④ It is always used in forward bias.
- ④ It is two terminal device
- ④ It converts electrical energy to light energy.



## Structure and Working of LED :-

### Structure:-

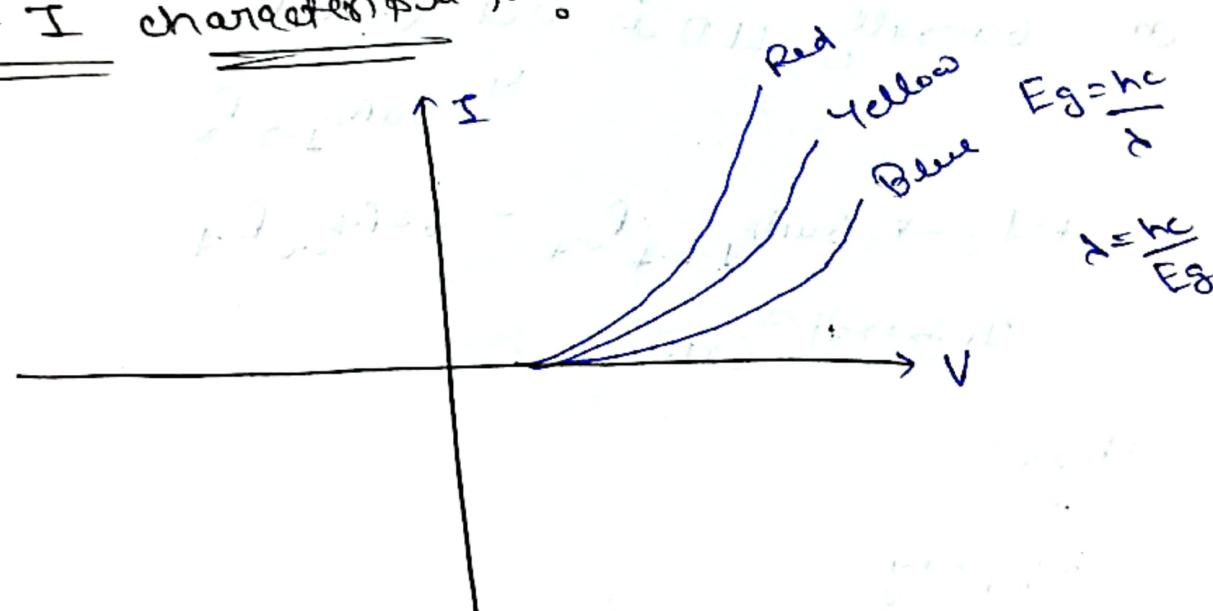


LEDs consist of P-N junction diode, which is connected in forward biasing that is P-type semiconductor is connected with the terminal of the battery and N-type semiconductor is -ve terminal of the battery.

## Working:

- When PN junction is forward bias, free e<sup>-</sup> and holes move towards opposite side, as a result free e<sup>-</sup> and holes recombine with each other or we can say that free e<sup>-</sup> in conduction band combines with holes in valence band.
- As a result, it emits light in the form of photon. This light energy, is in the visible range (4000 Å - 7000 Å) and the energy of the light is given by.  $E_g = h\nu = hc/\lambda$

## V-I characteristics:

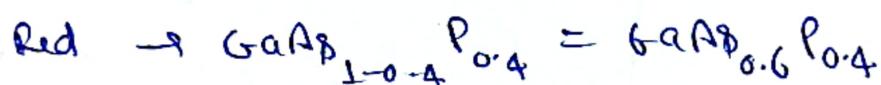


- The V-I characteristics of LED is shown in diagram which is similar to normal PN junction.
- when applied voltage is less than potential barrier, then the current will be zero. if applied voltage is greater than potential barrier then the current increasing by increasing voltage.

④ when  $\delta$  is less, Eg is more.  
therefore red is emitted for small voltage and  
blue is emitted for large voltage.

### Advantage of LED :-

- ① Long life (no filament)
- ② fast action
- ③ Low operational voltage.
- ④ Bandwidth is small.
- ⑤ Cheaper.
- ⑥ Generally LED is used  $\text{GaAsP}$   
 $\downarrow$   
 $\text{GaAs}_{1-x}\text{P}_x$



Infrared  $\rightarrow$   $\text{GaAs}$

### Uses :-

- ① Display
- ② Optical communication
- ③ Surgical lamp (sterilization)
- ④ Navigation light in maritime.

### Quantum efficiency of LED :-

- ① Internal

$$IQE = \frac{\text{No. of photons out from LED}}{\text{No. of electrons injected into LED}}$$

$$\text{IQE} = \frac{1}{n(n+1)^2}$$

internal quantum efficiency

$n = \text{refractive index of that material}$

$$EQE = \frac{\text{IQE}}{\text{External QE}} \times \text{Extraction coefficient}$$

Ques A LED has  $5 \times 10^{17}$  electrons injected per sec and it generate  $4 \times 10^{17}$  photons. calculate IQE.

Sol

$$IQE = \frac{4 \times 10^{17}}{5 \times 10^{17}} = 0.8$$

$$= 80\%$$

Ques An LED has IQE of 90%. due to optical losses and internal reflections, only 50% of the internally generated photons are able to escape as usual light. calculate EQE.

Sol

$$\begin{aligned} EQE &= \text{IQE} \times \text{extraction coefficient} \\ &= 0.9 \times 0.5 \\ &= 0.45 \\ &\approx 45\% \end{aligned}$$

Hence, external quantum efficiency is 45%.

Ques An LED operate with current of 20mA and emits a photon with an average energy of 2eV. The EQE = 40%. calculate optical power output.

Soln

$$\text{Optical Power Output} = \text{EQE} \times \text{Current} \times \text{Energy}$$
$$= 0.40 \times 20 \times 10^{-3} \text{ A} \times 2 \text{ eV}$$
$$= 0.16 \text{ mW}$$

It is not safe to touch it as it can burn your skin. And for dangerous information you have to speak with your physics teacher.

$$\text{Optical Power Output} = \text{EQE} \times \text{Current} \times \text{Energy}$$
$$= 0.40 \times 20 \times 10^{-3} \text{ A} \times 2 \text{ eV}$$

If the formula is wrong then tell me.

# Unit 3

## Difference b/w Classical & Quantum Mechanic

### Classical

- ① Classical mechanics is a macroscopic physics.
- ② Classical mechanics is based on Newton's law.
- ③ Classical mechanics is a definite physics.
- ④ Classical mechanics shows the wave nature of light.
- ⑤ Classical mechanics is able to explain interference, diffraction, polarization etc.

### Quantum

- ① Quantum mechanics is a microscopic physics.
- ② Quantum mechanics is based on Planck's theory of radiation.
- ③ Quantum mechanics is a probable physics.
- ④ Quantum mechanics shows wave nature as well as particle nature.
- ⑤ Quantum mechanics is able to explain photoelectric effect, Compton effect, black body radiation etc.

### Inadequacy or failure of classical Mechanics

- ⇒ Classical mechanics could not explain the stability of atom.

- ⇒ It could not explain black body radiation spectrum
- ⇒ It could not explain Compton effect, photoelectric effect
- ⇒ It could not explain the discrete energy levels of atom.

Black body radiation: A black body is one which completely absorbs the all incident radiation.

Eg :-

Black body Radiation? The radiation emitted by the black body when it is placed in a constant high temperature known as black body radiation.

### Plank's Theory of Quantum Mechanics

In 1900, Plank introduce the revolutionary theory of radiation known as quantum theory of radiation.

He made the following assumptions:-

- ① A black body consist of large number of small oscillating particles.
- ② The radiation emitted by the black body is in the form of discrete energy packets called Quanta / Photons
- ③ The energy of one photon ( $E$ ) =  $h\nu = \frac{hc}{\lambda}$
- ④ The black body either absorb or emit radiation which is integral multiple of ' $h\nu$ ', i.e.  $E = nh\nu$  ( $n=1, 2, 3, \dots$ )

### Wave Particle Duality

In some phenomena, like an interference, diffraction, polarization light behaves like a wave and in some other phenomena like in photoelectric effect, compton effect, Black body radiation light behave like a particle. It means light has a dual nature which is called wave particle duality.

## De-Broglie Hypothesis

"A moving particle is always associated with a wave" known as Matterwave. This is known as De-Broglie Hypothesis.

$$\text{And, } \lambda = \frac{h}{mv} = \frac{h}{p} \rightarrow \text{momentum of particle}$$

According to de-Broglie

### Other forms of De-Broglie wavelengths

- i) assume K.E. (kinetic energy of particle) =  $K$

$$\therefore \lambda = \frac{h}{mv} = \frac{h}{\sqrt{2mK}} = \frac{h}{\sqrt{\frac{1}{2} \times 2mK}}$$

$$\therefore \lambda = \frac{h}{\sqrt{2mK}}$$

- ii) If a particle is a charged particle of charge  $q$ , and accelerated by a potential difference  $V$  (volt).  $\therefore K = qV$

$$\text{as } \lambda = \frac{h}{\sqrt{2mK}} = \frac{h}{\sqrt{2mqV}}$$

- Ques: Find the De-Broglie wavelength of an electron accelerated by a potential difference  $V$  volt.

$$\text{for ex., } \lambda_c = \sqrt{\frac{150}{V}} \text{ Å} = \frac{12.26}{\sqrt{V}} \text{ Å}$$

→ If a particle is a gaseous molecule in thermal equilibrium,

$$K = \text{Boltzmann's constant} = 1.38 \times 10^{-23} \text{ J/K}$$

$$\lambda = \frac{h}{\sqrt{2mK}}$$

↳ Boltzmann's constant  
Energy

$$\therefore \lambda = \frac{h}{mv} = \frac{h}{\sqrt{2mk}} = \frac{h}{\sqrt{3mKT}}$$

↓  
Boltzmann's constant

② If a particle having rest mass  $m_0$  moving with velocity 'v' which is comparable to 'c' then its relativistic mass is

$$m = m_0$$

$$\sqrt{1 - \frac{v^2}{c^2}}$$

$$\therefore \lambda = \frac{h}{mv} = \frac{h}{m_0 v} \sqrt{1 - \frac{v^2}{c^2}}$$

## Properties of Matter wave

The properties of waves are

- ① The De-Broglie wavelength associated with lighter particle is greater than the heavier particle.
- ② The De-Broglie wavelength associated with slow moving particle is greater than fast moving particle.
- ③ If  $v=0$ ,  $\lambda=\infty$   
 & if  $v=\infty$ ,  $\lambda=0$  } i.e. particle should move with finite velocity
- ④ Matter wave is associated with charged particle as well as neutral particles.
- ⑤ The velocity of matter wave is not constant like electro-magnetic wave

To prove  $v_p = \frac{c^2}{v}$

$v_p$  = matter wave velocity

$c$  = speed of light

$v$  = particle velocity

The energy of a photon  $E = h\nu = \frac{hc}{\lambda}$

$$\therefore \nu = \frac{E}{h}$$

$$\therefore \nu = \frac{mc^2}{h} \quad \left[ \text{by Einstein energy mass relation } E = mc^2 \right]$$

If  $v_p$  is the wave velocity,

$$\text{then } v_p = \frac{\nu \lambda}{c} = \frac{mc^2}{h} \times \frac{h}{mv}$$

$$\therefore v_p = \frac{c^2}{v}$$

Since,  $v < c$

$$\therefore v_p = \frac{c^2}{v} > c \quad (\text{which is not possible})$$

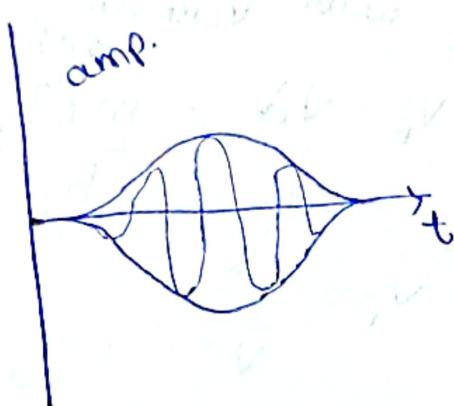
Since  $v$  is less than  $c$ , therefore  $v_p = \frac{c^2}{v}$

which is always greater than  $c$  which is not possible, moving particle

Hence, it shows matter/wave is not associated with single wave, i.e. moving particle is associated with wave group or wave packet.

Wave Group or Wave Packet?

The superposition of number of waves ~~oscillate~~  
of slightly different frequencies and wavelengths  
associated with moving particle known as  
wave group or wave packet.



- ④ Particle certainly like the wave packet

~~Wave Velocity or Phase velocity ( $v_p$ )~~

when a monochromatic wave travels in a medium then the velocity of that wave is known as wave velocity or phase velocity ( $v_p$ )

where 
$$v_p = \frac{\omega}{k}$$

$\Rightarrow \omega \rightarrow$  angular frequency  $= 2\pi\nu$   
 $\Rightarrow k \rightarrow$  propagation constant  $= \frac{2\pi}{\lambda}$

or  $\omega = 2\pi\nu$ ,  $k = \frac{2\pi}{\lambda}$

$$v_p = \frac{\omega}{k} = \frac{2\pi\nu}{2\pi/\lambda} = \nu\lambda$$

## Group Velocity ( $V_g$ ) :-

The velocity of the wave group associated with moving particle is known as group velocity.

$$V_g = \frac{\partial \omega}{\partial k} = \frac{\omega_1 - \omega_2}{k_1 - k_2} = \frac{\text{difference in } \omega}{\text{difference in } k}$$

Relation b/w Group velocity ( $V_g$ ) & wave velocity ( $V_p$ )

$$V_p = \frac{\omega}{k}$$

$$\omega = V_p k$$

$$d\omega = V_p dk + k dV_p$$

$$\frac{d\omega}{dk} = V_p + k \frac{dV_p}{dk}$$

$$V_g = V_p + k \frac{dV_p}{dk} \cdot \frac{dk}{dk} \quad \text{--- (1)}$$

$$\text{as } \lambda = \frac{2\pi}{k}$$

$$\therefore \frac{dk}{dk} = -\frac{2\pi}{\lambda^2}$$

put in (1)

$$V_g = V_p + k \frac{dV_p}{dk} \left( -\frac{2\pi}{\lambda^2} \right) = V_p - \frac{2\pi}{\lambda} \frac{dV_p}{d\lambda}$$

$$V_g = V_p - \lambda \frac{dV_p}{d\lambda}$$

$\therefore (V_g < V_p \text{ always})$

$\Rightarrow$  for Non-dispersive Medium,

$$\frac{dV_p}{d\lambda} = 0 \quad \therefore V_g = V_p$$

To prove  $V_g = V$

Consider a particle having rest mass ' $m_0$ ' moving with velocity  $v$  which is comparable to 'c'

$$\text{Then } \Rightarrow m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} \rightarrow 0$$

if  $\omega$  is the angular velocity,

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

$$\omega = \frac{2\pi m_0 c^2}{h} \rightarrow \omega = \frac{2\pi m_0 c^2}{h \left(1 - \frac{v^2}{c^2}\right)^{1/2}}$$

$$\frac{d\omega}{d\nu} = \frac{2\pi m_0 c^2}{h} \frac{d}{d\nu} \left(1 - \frac{v^2}{c^2}\right)^{-1/2}$$

$$\frac{d\omega}{dv} = \frac{2\pi m_0 c^2}{h} \left(\frac{1}{2}\right) \left(1 - \frac{v^2}{c^2}\right)^{-3/2} \left(-\frac{2v}{c^2}\right)$$

$$\frac{d\omega}{dv} = \frac{2\pi m_0 v}{h} \left(1 - \frac{v^2}{c^2}\right)^{-3/2}$$

$$K = \frac{2\pi}{\lambda} = \frac{2\pi mv}{h}$$

$$K = \frac{2\pi m_0 v}{h \left(1 - \frac{v^2}{c^2}\right)^{1/2}}$$

$$\frac{dK}{dv} = \frac{d}{dv} \left[ \frac{2\pi m_0 v}{h \left(1 - \frac{v^2}{c^2}\right)^{1/2}} \right]$$

$$\frac{dK}{dv} = \frac{2m_0 \pi}{h} \frac{d}{dv} \left[ \frac{v}{\left(1 - \frac{v^2}{c^2}\right)^{1/2}} \right]$$

$$\frac{dK}{dv} = \frac{2\pi m_0}{h} \left[ \left(1 - \frac{v^2}{c^2}\right)^{-1/2} + v \left(\frac{1}{2}\right) \left(1 - \frac{v^2}{c^2}\right)^{-3/2} \left(-\frac{2v}{c^2}\right) \right]$$

$$\frac{dK}{dv} = \frac{2\pi m_0}{h \left(1 - \frac{v^2}{c^2}\right)^{3/2}} \quad \text{--- (3)}$$

then  $v_g = \frac{d\omega}{dk} = \frac{d\omega/dv}{dK/dv} = \frac{\frac{2\pi m_0 v}{h} \left(1 - \frac{v^2}{c^2}\right)^{-3/2}}{\frac{2\pi m_0 \left(1 - \frac{v^2}{c^2}\right)^{-3/2}}{h}}$

$\therefore \boxed{v_g = v}$  → which shows that group velocity is equal to particle velocity.

# Wave function ( $\Psi$ ) and its physical significance

⇒ Probability Amplitude

it is complex quantity

$$\Psi = A + iB \quad \downarrow \quad \text{complex conjugate}$$
$$\Psi^* = A - iB \quad \leftarrow \quad \text{of } \Psi$$

$$|\Psi|^2 = \Psi \Psi^*$$

$$|\Psi|^2 = (A+iB)(A-iB)$$

$$|\Psi|^2 = A^2 + B^2 \Rightarrow \text{real}$$

name ⇒ Probability density ⇒ Probability of finding  
a particle in wave  
packet at a particular time, at a  
particular point.

Ex.  $\iiint_{-\infty}^{\infty} |\Psi|^2 dx dy dz = 1$

⇒ The quantity whose variation with  
matter wave known as wave function ( $\Psi$ ),  
it is also probability amplitude of  
matter wave.

it is a complex quantity and related  
to  $|\psi|^2$  known as probability density.

$|\psi|^2 = \psi\psi^*$  which is a real quantity,

according to max Born,  $|\psi|^2$  gives the

Probability of finding the particle in

a wave packet at a particular time and

at a particle point.

Since, particle certainly lie the wave packet.

$$\iiint_{-\infty}^{\infty} |\psi|^2 dx dy dz = 1$$

This condition

is known as normalization condition.

Conditions for Acceptable wave function

(a)  $\psi$  must be finite.

(b)  $\psi$  must be single valued.

(c)  $\psi$  must be continuous.

Schrodinger's wave Equation

(1) Schrodinger's Time independent wave equation.

(2) Schrodinger's Time dependent wave equation.

→ To study the wave nature of moving particle,

Schrodinger derived an equation known as Schrodinger's wave equation.

It is of two type written previously.

① Schrodinger's Time independent wave equation:

$\vec{\nabla}$  : Deloperator (3-dimensional differential operator)

$$\vec{\nabla} = \frac{\partial \hat{i}}{\partial x} + \frac{\partial \hat{j}}{\partial y} + \frac{\partial \hat{k}}{\partial z}$$

$$\vec{\nabla} \cdot \vec{\nabla} = (\vec{\nabla})^2 = \left( \frac{\partial \hat{i}}{\partial x} + \frac{\partial \hat{j}}{\partial y} + \frac{\partial \hat{k}}{\partial z} \right) \left( \frac{\partial \hat{i}}{\partial x} + \frac{\partial \hat{j}}{\partial y} + \frac{\partial \hat{k}}{\partial z} \right)$$

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

general wave equation,

$$\nabla^2 \psi = \frac{1}{v^2} \frac{\partial^2 \psi}{\partial t^2}$$

The differential wave equation for matter is:

$$\nabla^2 \psi = \frac{1}{v^2} \frac{\partial^2 \psi}{\partial t^2} \quad \text{--- (1)}$$

Solution of equation (1) is

$$\psi = \psi_0 e^{-i \omega t} \quad \text{--- (2)}$$

differentiating eq(3) with respect to  $t$ :

$$\frac{\partial \psi}{\partial t} = \psi_0 \frac{\partial}{\partial t} e^{-i\omega t}$$

$$\frac{\partial \psi}{\partial t} = -\psi_0 i\omega e^{-i\omega t}$$

differentiating again w.r.t.  $t$ :

$$\frac{\partial^2 \psi}{\partial t^2} = \psi_0 (-i\omega)^2 e^{-i\omega t} = (-i\omega)^2 \psi_0 e^{-i\omega t}$$

$$\frac{\partial^2 \psi}{\partial t^2} = -\omega^2 \psi \quad \text{--- (3)}$$

$$\nabla^2 \psi = \frac{1}{v^2} \frac{\partial^2 \psi}{\partial t^2} \xrightarrow{\text{put here}} \nabla^2 \psi = \frac{1}{v^2} (-\omega^2 \psi)$$

$$\nabla^2 \psi = \frac{1}{v^2} (-\omega^2 \psi) + \frac{1}{v^2} \nabla^2 \psi$$

$$(\nabla^2) \psi = \frac{1}{v^2} (-4\pi^2 \delta^2) \psi$$

$$= \frac{1}{v^2} \left( -4\pi^2 \frac{v^2}{\delta^2} \psi \right)$$

$$\nabla^2 \psi = -\frac{4\pi^2}{\delta^2} \psi$$

$$\left. \begin{aligned} & \nabla^2 \psi + \frac{4\pi^2}{\delta^2} \psi = 0 \\ & \nabla^2 \psi + \frac{4\pi^2 m^2 v^2}{h^2} \psi = 0 \end{aligned} \right\} \quad \text{--- (4)}$$

Ans: ①

$$\textcircled{ii} \quad \Psi = e^{-ikx}$$

Normalize both equations.

If  $E = \text{Total energy}$

$V = \text{Potential energy}$

$\therefore \text{kinetic energy} = E - V$

$$\frac{1}{2}mv^2 = (E - V)$$

$$mV^2 = 2m(E - V)$$

Putting on equation ④, we get

$$\nabla^2 \Psi + \frac{4\pi^2}{n^2} \times \frac{2m(E - V)}{\hbar^2} \Psi = 0$$

$$\nabla^2 \Psi + \frac{8\pi^2 m(E - V)}{n^2} \Psi = 0$$

} standard form of Schrödinger's wave equation.

for free particle,  $V=0$

$$\therefore \nabla^2 \Psi + \frac{8\pi^2 m E}{n^2} \Psi = 0$$

$$\text{define } \frac{\hbar}{2\pi} = \frac{n}{r}$$

$$\hbar = \frac{\hbar}{2\pi}(2\pi)$$

$$\hbar^2 = \frac{\hbar^2}{4\pi^2}$$

Now,

$$\boxed{\nabla^2 \Psi + \frac{8\pi^2 m(E - V)}{\hbar^2(4\pi^2)} \Psi = 0}$$

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

Schrodinger's time dependent wave Eqn

The differential wave equation for matter is:

$$\nabla^2 \psi = \frac{1}{v^2} \frac{\partial^2 \psi}{\partial t^2} \quad \text{--- (1)}$$

solution of equation (1) is:

$$\psi = \psi_0 e^{-i\omega t} \quad \text{--- (2)}$$

partial differentiating (2) w.r.t. 't',

$$\frac{\partial \psi}{\partial t} = \psi_0 (-i\omega) e^{-i\omega t}$$

$$\frac{\partial \psi}{\partial t} = -i\omega \psi$$

$$\frac{\partial \psi}{\partial t} = -i(2\pi\nu) \psi$$

$$\frac{\partial \psi}{\partial t} = -i\left(\frac{2\pi E}{\hbar}\right) \psi$$

$$\frac{\partial \psi}{\partial t} = -\frac{i}{\hbar} E \psi$$

$$E \psi = -\frac{\hbar}{i} \frac{\partial \psi}{\partial t}$$

$$E \psi = i\hbar \frac{\partial \psi}{\partial t} \quad \text{--- (3)}$$

We know that Schrodinger's wave equation is

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

$$\nabla^2 \psi = - \frac{2m}{\hbar^2} (E \psi - V \psi) = 0$$

$$-\frac{\hbar^2}{2m} \nabla^2 \psi = E \psi - V \psi$$

$$V \psi - \frac{\hbar^2}{2m} \nabla^2 \psi = E \psi$$

$$-\frac{\hbar^2}{2m} \nabla^2 \psi^2 + V \psi = i \hbar \frac{\partial \psi}{\partial t}$$

time dependent  
of Schrodinger's  
wave equation.

## Heisenberg's Uncertainty Principle

According to Heisenberg Uncertainty Principle,

It is impossible to measure the exact position and momentum of a microscopic particle simultaneously.

acc. to Heisenberg,

$$\Delta x \cdot \Delta p \geq \hbar / 4\pi$$

$$\Delta E \cdot \Delta t \geq \hbar / 4\pi$$

$$\Delta J \cdot \Delta \theta \geq \hbar / 4\pi$$

$\Delta x \rightarrow$  uncertainty in position

$\Delta p \rightarrow$  uncertainty in momentum

$\Delta E \rightarrow$  uncertainty in energy

$\Delta t \rightarrow$  uncertainty in time

$\Delta J \rightarrow$  uncertainty in angular momentum

$\Delta \theta \rightarrow$  uncertainty in angle

Ques: If the uncertainty in position of  $e^-$  is  $4 \times 10^{-10} m$ , calculate uncertainty in momentum.

Sol  $\Delta x \cdot \Delta p = h/4\pi$

$$\Delta p = \frac{6.6 \times 10^{-34}}{4 \times 3.14 \times 4 \times 10^{-10}} = 2.31 \times 10^{-25} \text{ kg m/sec}$$

Ques: The lifetime of an excited state of nucleus is  $10^{-12}$  sec. what is the uncertainty in energy.

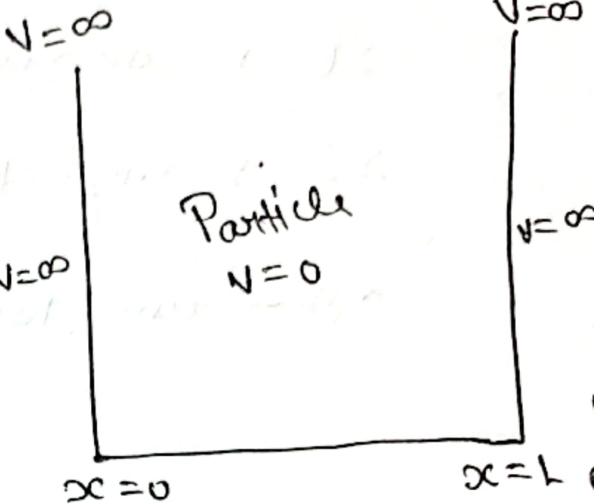
Sol  $\Delta E = \frac{6.6 \times 10^{-34}}{4 \times 3.14 \times 10^{-12}} = 5.25 \times 10^{-23} J$

# Particle in 1 Dimensional Infini*t* Potential box

$V = 0$  (Inside the box)

$$x > 0 \text{ & } x < L$$

$V = \infty$  at walls & outside the box (i.e.  $x \leq 0$  &  $x \geq L$ )



Consider a 1 dimensional infinite potential box of width 'L'. Suppose particle is inside the box and it is free to move in one dimensional than the expression for potential energy for a particle is given by:

$V = 0$  (Inside the box)  
(i.e.  $x > 0$  &  $x < L$ )

and  $V = \infty$  at walls and outside the box  
(i.e.  $x \leq 0$  &  $x \geq L$ )

The Schrödinger's wave for the given system can be written as,

$$\nabla^2 \psi + \frac{8\pi^2 m}{h^2} (E - V) \psi = 0$$

Inside the box,  $V=0$

$$\therefore \nabla^2 \psi + \frac{8\pi^2 m}{h^2} E \psi = 0$$

$$\nabla^2 \psi + \frac{8\pi^2 m E}{h^2} \psi = 0$$

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

$$k^2 = \frac{8\pi^2 m E}{h^2} \quad \text{--- (3)}$$

$\Rightarrow$  The solution of eqn (2) can be written as

$$\boxed{\psi = A \sin kx + B \cos kx} \quad \text{--- (4)}$$

where  $A$  and  $B$  are the constants and can be determined by the boundary conditions

(\*) Applying first boundary condition:

when  $x=0, \psi=0$

$$\text{as } \psi = A \sin kx + B \cos kx$$

$$0 = A \sin 0 + B \cos 0$$

$$B = 0$$

$$\therefore \boxed{\psi = A \sin kx} \quad \text{--- (5)}$$

④ Applying Second boundary condition,  
when  $x=L$ ,  $\psi=0$

$$\text{as } \psi = A \sin(kx)$$

$$0 = A \sin(kL)$$

$$\therefore \sin(kL) = 0$$

$$\therefore kL = n\pi$$

(as B already 0,  
hence A can't be  
zero.)

$$K = \frac{n\pi}{L} \quad \text{--- (6)}$$

squaring on both sides

$$K^2 = \frac{n^2\pi^2}{L^2}$$

$$K^2 = \frac{n^2\pi^2}{L^2}$$

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

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

for ground state,  $n=1$

$$E_1 = \frac{n^2 h^2}{8m L^2} = \frac{h^2}{8m L^2}$$

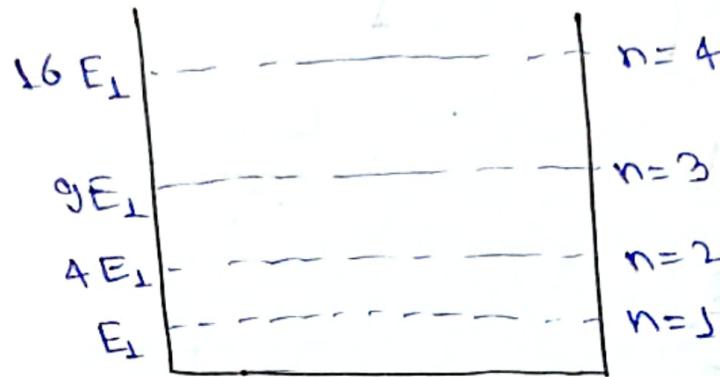
$$E_1 = \frac{h^2}{8m L^2}$$

→ for first excited state (i.e.  $n=2$ )

$$E_2 = \frac{4 h^2}{8 m L^2} = 4 E_1$$

→ for second excited state (i.e.  $n=3$ )

$$E_3 = \frac{9 h^2}{8 m L^2} = 9 E_1$$



Constant  $A$  can be determined with the help  
of normalization condition.

$$\Psi = A \sin(kx)$$

$$\Psi = A \sin\left(\frac{n\pi x}{L}\right)$$

$$\therefore \Psi^* = A \sin\left(\frac{n\pi x}{L}\right)$$

$$|\Psi|^2 = \Psi \Psi^* = A^2 \sin^2\left(\frac{n\pi x}{L}\right)$$

④ Applying Second boundary condition,

when  $x=L$ ,  $\psi=0$

$$\text{as } \psi = A \sin(kx)$$

$$0 = A \sin(kL)$$

$$\therefore \sin(kL) = 0$$

$$\therefore kL = n\pi$$

(as B already 0,  
hence, A can't be  
zero.)

$$\boxed{K = \frac{n\pi}{L}} \quad \rightarrow \quad ⑥$$

Squaring on both side

$$K^2 = \frac{n^2\pi^2}{L^2}$$

$$\hookrightarrow K^2 = \frac{n^2\pi^2}{L^2}$$

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

$$\boxed{E = \frac{n^2 h^2}{8m L^2}}$$

$\Rightarrow$  for ground state,  $n=1$

$$E_1 = \frac{n^2 h^2}{8m L^2} = \frac{h^2}{8m L^2}$$

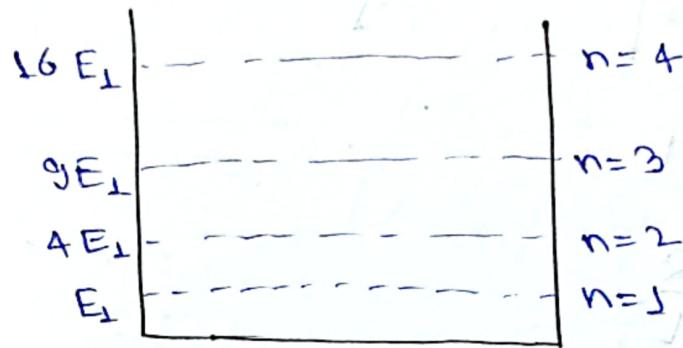
$$E_1 = \frac{h^2}{8m L^2}$$

→ for first excited state (i.e.  $n=2$ )

$$E_2 = \frac{4 h^2}{8mL^2} = 4 E_1$$

→ for second excited state (i.e.  $n=3$ )

$$E_3 = \frac{9 h^2}{8mL^2} = 9 E_1$$



Constant A can be determined with the help of normalization condition

$$\Psi = A \sin(kx)$$

$$\Psi = A \sin\left(\frac{n\pi x}{L}\right)$$

$$\therefore \Psi^* = A \sin\left(\frac{n\pi x}{L}\right)$$

$$|\Psi|^2 = \Psi \Psi^* = A^2 \sin^2\left(\frac{n\pi x}{L}\right)$$

$$|\psi|^2 = \frac{A^2}{2} \left[ 1 - \cos\left(\frac{2n\pi x}{L}\right) \right]$$

$$\int_0^L |\psi|^2 dx = \frac{A^2}{2} \left[ x - \frac{\sin\left(\frac{2n\pi x}{L}\right)}{\frac{2n\pi}{L}} \right]_0^L$$

$$1 = \frac{A^2}{2} \left[ L - 0 \right]$$

$$\Rightarrow 1 = \frac{A^2}{2} \times L$$

$$\Rightarrow A^2 = \frac{2}{L}$$

$$\Rightarrow A = \sqrt{\frac{2}{L}}$$

$$\therefore \text{or } \psi = A \sin kx$$

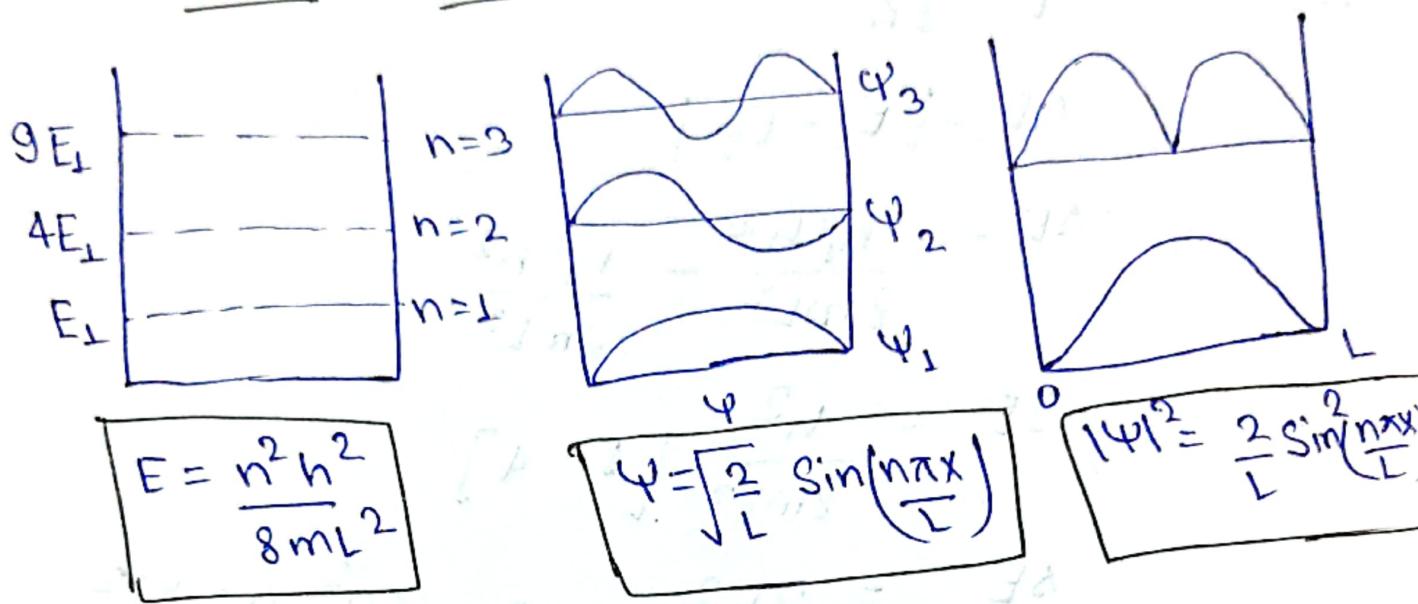
$$\boxed{\psi = \sqrt{\frac{2}{L}} \sin\left(\frac{n\pi x}{L}\right)}$$



$$\boxed{|\psi|^2 = \frac{2}{L} \sin^2\left(\frac{n\pi x}{L}\right)}$$



The energy ( $E$ ), wave function ( $\Psi$ ) and probability density  $|\Psi|^2$  of a particle in one-dimensional infinite potential boxes represented as:



⇒ When the particle is in first energy state (i.e.  $n=1$ ), then the probability of finding the particle is maximum at  $\frac{L}{2}$ , and minimum at 0 and  $L$ .

⇒ and when the particle is in first excited state (i.e.  $n=2$ ) than the probability of finding the particle is maximum at  $\frac{L}{4}$  and  $\frac{3L}{4}$ , and minimum at  $\frac{L}{2}$ .

Ques % Calculate the energy difference between the ground state and first excited state for an electron in one-dimensional rigid box of length  $1\text{A}$ .

Sol %

$$L = 1\text{A}$$

$$\Delta E = |E_1 - E_2|$$

$$\Delta E = \frac{n_1^2 h^2}{8mL^2} - \frac{n_2^2 h^2}{8mL^2}$$

$$\Delta E = \frac{h^2}{8mL^2} [1 - 4]$$

$$\Delta E = \frac{3h^2}{8mL^2} = \frac{3 \times (6.6)^2 \times (10^{-34})^2}{8 \times 9.1 \times 10^{-31} \times 10^{-20}}$$

$$\Delta E = \frac{3 \times (6.6)^2 \times 10^{-68+51}}{9.1 \times 8} \text{ J}$$

$$\Delta E = \frac{3 \times (6.6)^2 \times 10^{-17}}{9.1 \times 8} \text{ J}$$

$$\Delta E = \frac{3 \times (6.6)^2 \times 10^{-17}}{9.1 \times 8 \times (1.6 \times 10^{-19})} \text{ eV}$$

$$\Delta E = 152.1 \text{ eV}$$