Body Centered Cubic Structure:-

* In BCC unit cell, 8 corner atoms and 1 body center atom are available.

* Each corner atom is shared by 8 adjacent unit cells.

* Body center atom completely belongs to a single unit cell.

No. of atoms per unit cell:

Corner atom $= 8 \times \frac{1}{8} = 1$

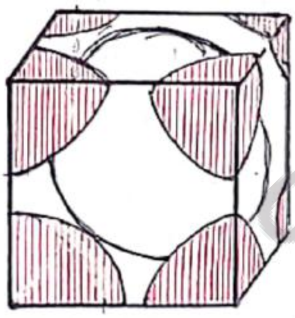
Body center atom = 1

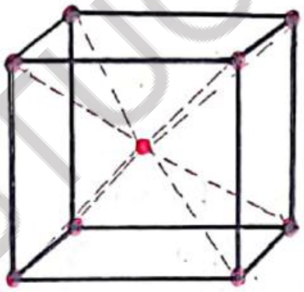
$\therefore$ Total no of atoms per unit cell $\} = 1+1 = \boxed{2}$

Co-ordination Number:-

In BCC each body centered atom is surrounded by 8 closest corner atom along its diagonal.

$\therefore$ Coordination Number $= \boxed{8}$

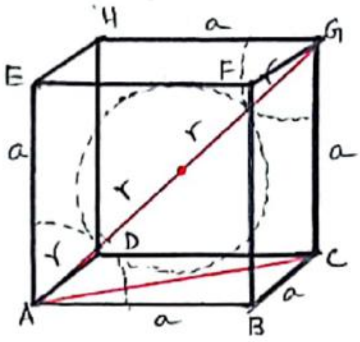




Atomic Radius (r):

* In BCC, closest and longest bond consider between any two corner atoms and body center atom along its body diagonal.

* From the diagram consider a body diagonal 'AG' of an unit cell.



From the diagram,

$\Delta ACG \quad AG^2 = AC^2 + CG^2$

WKt, $AG = 4r, \quad CG = a$

and $AC^2 = AB^2 + BC^2$

In which, $AB = a, \quad BC = a$

$\therefore AG^2 = AB^2 + BC^2 + CG^2$

$(4r)^2 = a^2 + a^2 + a^2$

$16r^2 = 3a^2$

$r^2 = \frac{3}{16}a^2$

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

Atomic Packing Factor:-

$$PF = \frac{\text{No. of atoms} \times \text{Vol. of an atom}}{\text{Vol. of unit cell}}$$

No. of atoms per unit cell $\} = 2$

Atomic radius $r = \frac{\sqrt{3}}{4}a$.

Volume of an unit cell $V = a^3$

$\therefore PF = \frac{2 \times 4/3\,\pi \left(\frac{\sqrt{3}}{4}a\right)^3}{a^3}$

$PF = \frac{\sqrt{3}\pi}{8} = 0.68$

(i.e) In BCC 68% space in an unit cell occupied by atoms and 32% of the space is vacant.

Face Centered Cubic [FCC]

* In FCC, structure, the unit cell has 8 corner atoms and one atom at the centre of each face.

* It is one of the Closely packed structures.

No. of atoms per unit cell:

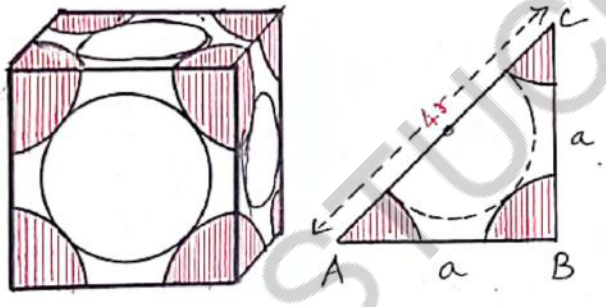
* In FCC unit cell, Corner atom is shared by 8 adjacent unit cells.

∴ No of corner atoms = $8 \times \frac{1}{8} = 1$

* Each face center atom shared by 2 other unit cells.

∴ No of face center atoms = $6 \times \frac{1}{2} = 3$.

∴ Total no of atoms per unit cell $= 1+3 = \boxed{4}$



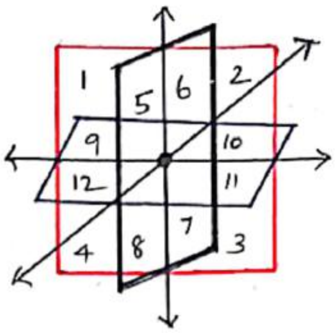
Co-ordination Number:-

*In FCC, each corner atom surrounded by 4 face center atom in an axis plane [x, y, z]

X-Plane [1,2,3,4], Y-Plane [5,6,7,8]

Z-Plane [9,10,11,12].

∴ Total no of nearest atoms $= 4+4+4 = \boxed{12}$



Atomic Radius:-

In FCC, each face center atom has a bond between two corner atom through its face diagonal.

In ΔABC,

$$AC^2 = AB^2 + BC^2$$
$$(4r)^2 = a^2 + a^2$$
$$16r^2 = 2a^2$$
$$r^2 = \frac{2a^2}{16}$$
$$r = \frac{\sqrt{2}a}{4}.$$

Atomic Packing Factor:

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

No. of atoms = 4

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

Volume $V = a^3$

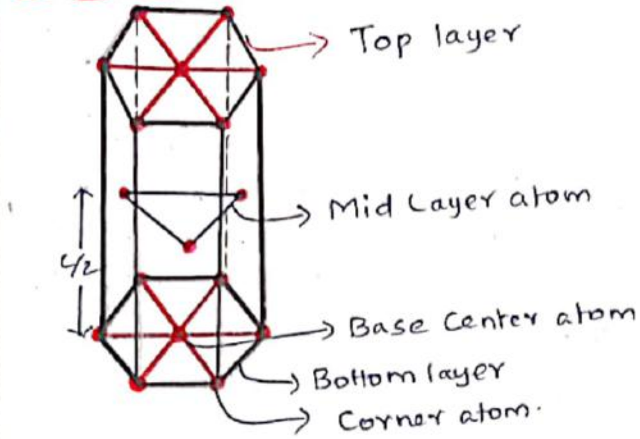
$$PF = \frac{4 \times \frac{4}{3}\pi r^3}{a^3}$$

$$PF = \frac{4 \times \frac{4}{3} \times \pi \left(\frac{\sqrt{2}a}{4}\right)^3}{a^3}$$

$$PF = \frac{\pi\sqrt{2}}{6} = 0.74$$

In FCC unit cell, 74% volume is occupied by atom, 26% is vacant.

Hexagonal Closed Pack



* Unit cell of HCP consists of 3 layers and 3 different atoms.

* It has one atom at each corner of the hexagon totally 12 corner atoms.

* One atom at the center of the hexagon plane (ie base).

∴ There are two base centre atoms.

* 3 atoms at $c/2$ distance from top or bottom. They are completely inside the unit cell.

No. of atoms per unit cell:

In HCP, each corner atom is shared by 6 unit cells.

∴ No. of corner atoms (in top layer) $= 6 \times \frac{1}{6} = 1$

III'ly we have same no. of atoms in bottom layer.

∴ Total no. of corner atoms $\} = 1+1 = 2$

Each base centred atom is shared by 2 unit cells.

∴ No. of base centre atom $= 2 \times \frac{1}{2} = 1$.

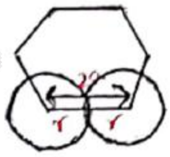
All 3 mid layer atoms completely placed inside an unit cell.

∴ No of mid layer atom = 3

∴ Total no. of atoms per unit cell $\} = 2+1+3 = \boxed{6}$

Atomic Radius:

Any two corner atoms form a closest bond by touching each other



∴ $2r = a$

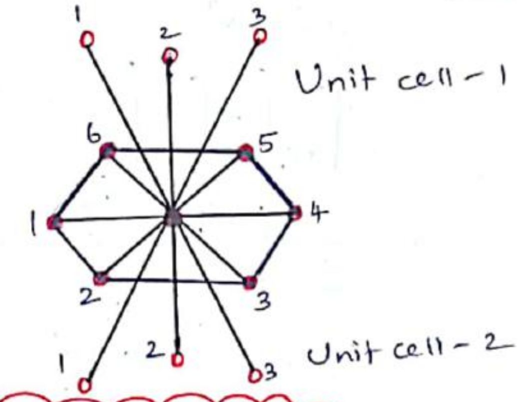
$r = a/2$

Coordination Number:

* A base center atom will touch all 6 surrounding corner atoms.

* And also, it is in contact with 3 mid layer atoms in the top unit cell and 3 mid layer atoms in the bottom unit cells.

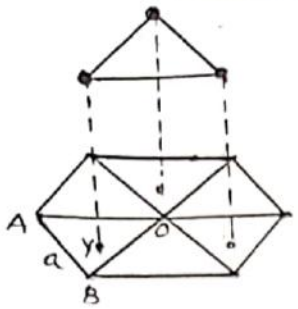
∴ Coordination no $= 3+3+6 = \boxed{12}$

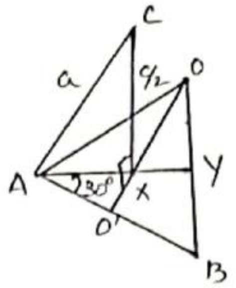


C/a Ratio Calculation:

Let 'c' be the height of the unit cell.

Consider a triangle ABO above which center atom 'c' lies at a distance $c/2$.





Here 'AY' is drawn ⊥r to 'BO' and 'x' is the inter point above which center atom is located.

In ΔABY

$$\cos 30^\circ = \frac{AY}{AB}$$

$$AY = AB\cos 30^\circ$$

$$AY = \frac{a\sqrt{3}}{2} \quad — ①$$

'x' is the center of ΔABO

$$\therefore Ax = \frac{2}{3}AY \quad — ②$$

$$Ax = \frac{2}{3}\frac{a\sqrt{3}}{2} = \frac{a}{\sqrt{3}} \quad — ③$$

In ΔAXC

$$AC^2 = Ax^2 + Cx^2$$

$$a^2 = \left[\frac{a}{\sqrt{3}}\right]^2 + \left[\frac{c}{2}\right]^2$$

$$a^2 = \frac{a^2}{3} + \frac{c^2}{4}$$

$$\frac{c^2}{4} = a^2 - \frac{a^2}{3} = \frac{3a^2 - a^2}{3}$$

$$\frac{c^2}{4} = \frac{2a^2}{3}$$

$$\frac{c^2}{a^2} = \frac{8}{3}$$

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

Packing Factor:

$$\left.\begin{array}{l}\text{Volume of an}\\ \text{unit cell}\end{array}\right\} = \text{Height} \times \text{Area of base}$$

$$= c \times 6 \times \text{Area of } \Delta ABO$$

$$= c\left[6 \times \frac{1}{2} \times \underset{(BO)}{\text{Base}} \times \underset{(AY)}{\text{Height}}\right]$$

$$= c \times 6 \times \frac{1}{2} \times a \times a\frac{\sqrt{3}}{2}$$

~~Volu~~

$$\text{Volume of unit cell} = \frac{3\sqrt{3}a^2c}{2}$$

$$\text{Vol. of atoms} = \frac{4}{3}\pi r^3 \times 6.$$

$$= \frac{4}{3}\cdot\pi\cdot\frac{a^3}{8} \times 6 = \pi a^3.$$

$$\left.\begin{array}{l}\text{Atomic Packing}\\ \text{Factor}\end{array}\right\} = \frac{\text{Vol. of atoms}}{\text{Vol. of unit cell.}}$$

$$APF = \frac{\pi a^3}{\frac{3\sqrt{3}a^2c}{2}} = \pi a^3 \times \frac{2}{3\sqrt{3}a^2c}$$

$$= \frac{2\pi}{3\sqrt{3}}\cdot\left[\frac{a}{c}\right]$$

$$= \frac{2\pi}{3\cancel{\sqrt{3}}}\cdot\frac{\cancel{\sqrt{3}}}{\sqrt{8}} = \frac{2\pi}{\sqrt{8} \times 3}.$$

$$= 0.74.$$

$$APF = 74\%.$$

∴ For HCP unit cell 74% space is atom and 26% space is vaccant.

Crystal Imperfections:-

If atoms in solid are not arranged in a perfectly regular manner, it is called defects in crystal.

Types:

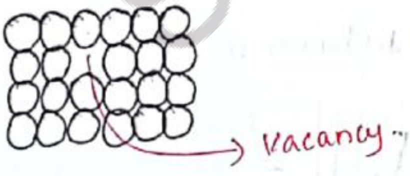
- * Point Defects,
  - Vacancies
  - Interstitial Defects
  - Impurity Defects.
  - ~~Impurit~~
- * Line Defects
  - Edge Dislocation
  - Screw Dislocation.
- * Surface Defects
  - Grain Boundaries
  - Tilt Boundaries
  - Twin Boundaries
  - Stacking Faults.
- * Volume Defects
  - Crack.

Point Defects:-

Due to imperfect packing of atoms during crystallisation.

Vacancies:-

It refers to a missing atom.



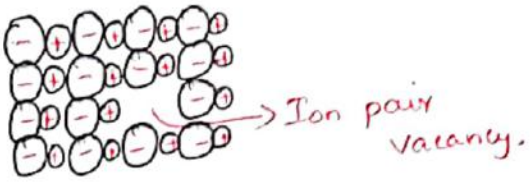
There are two types of vacancies

(i) Schottky Defect.

(ii) Frenkel Defect.

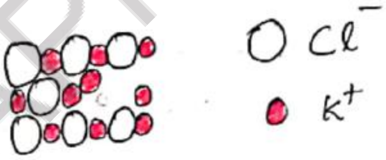
Schottky Defect:

It refers to the missing of a pair of positive and negative ions in an ionic crystal.



Frenkel Defect:

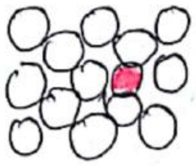
A vacancy associated with interstitial impurity is called Frenkel defect.

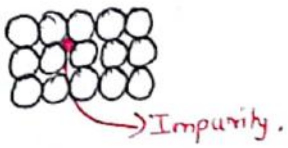


Interstitial Defect:

Self Interstitial

If an atom from same crystal occupies interstitial site it is called self interstitial


Self Interstitial



Foreign Interstitial

Foreign Interstitial

If an impurity atom occupies interstitial site it is called foreign interstitial.

Impurities:

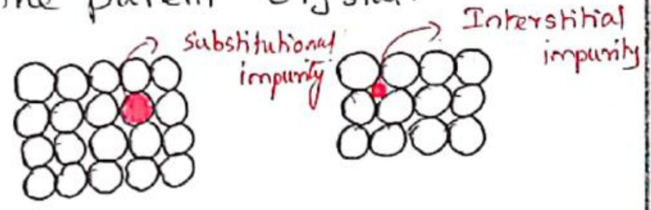
Adding of foreign atoms to crystal lattice is known as impurity defects

Substitutional impurity Defect:

* Foreign atom replaces the parent atom.

Interstitial Impurity Defect:

Small size foreign atom occupies the empty space in the parent crystal.



Line Defect:

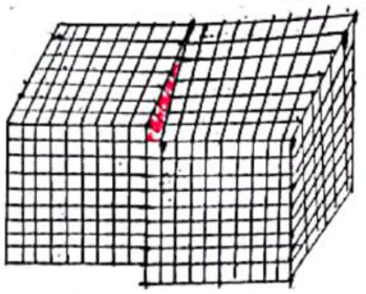
A portion of a line of atoms is missing or displaced from its regular size.

Types:

Edge Dislocation.
Screw Dislocation.

Edge Dislocation:

In this type one of the atomic planes does not extend through the entire crystal.



Screw Dislocation:

It is due to a displacement of atoms in one part of a crystal relative to rest of the crystal.

Surface Defects:

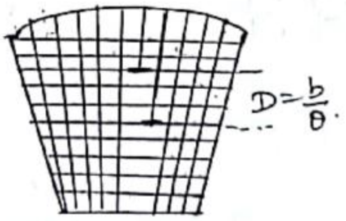
In this type, the defects takes place in the surface of crystal.

Grain Boundary:

It is the boundary in the grains at which the atomic arrangement one side is mirror image of the atoms on the other side

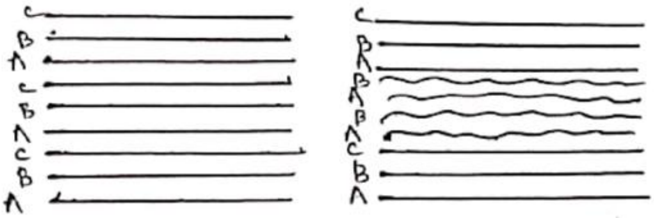
Tilt Boundary:

It is an array of parallel edge dislocation



Stacking Faults:

Whenever the stacking of atoms is not in proper sequence throughout the crystal, defect is called stacking fault.



Plastic Deformation Mechanism:-

Plastic Deformation of a single crystal occurs in two ways

1. Slip
2. Twinning.

Slip:-

The deformation by slip takes place when one part of the crystal moves or glides over another part along certain planes.

Mechanisms of Slip

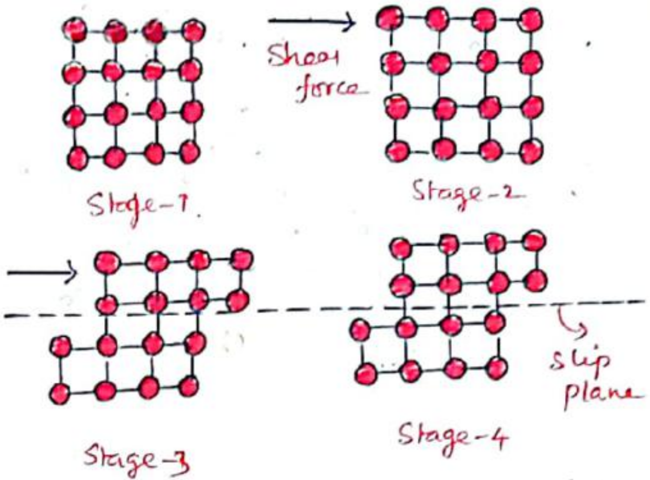
There are 4 stages during plastic deformation of single crystal by the slip.

Stage: 1 → Perfect crystal without slip.

Stage: 2 → Deforming shear force is applied to the crystal.

Stage: 3 → Slip taking place along the slip plane

Stage: 4 → Permanent deformation when deforming forces are removed.



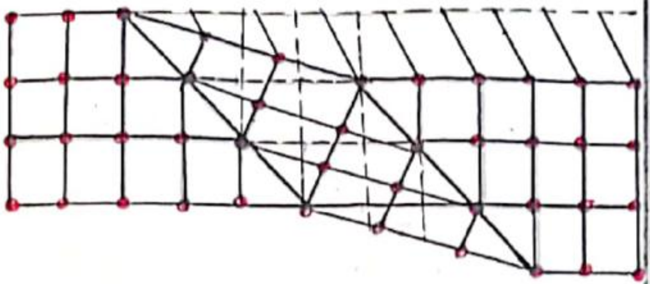
The particular crystallographic planes where slip occurs are called slip planes. The preferable direction along which slip occurs is called the slip direction.

Twinning:-

The shear forces produce atomic displacements such that the deformed lattice forms a mirror image of the undeformed lattice.

(ie) The atoms on one side of the plane location is in mirror image position of the atoms on the other side.

The crystallographic plane of symmetry between the deformed and undeformed parts of the metal lattice is called the twinning plane.



Types of Twins:

1. Mechanical Twins
2. Annealing Twins.

Mechanical Twins:-

These twins are produced by mechanical deformation. These twins are produced in BCC & HCP crystals.

Annealing Twins:-

These twins are produced by annealing process. The are usually broader and produced mostly in FCC crystals.

Expression for the Electrical Conductivity:

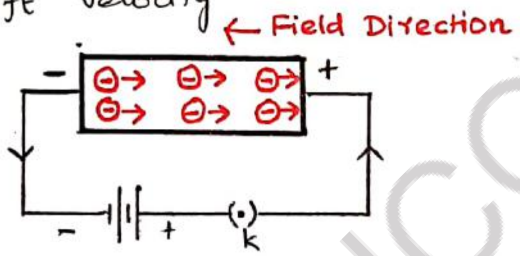
Definition:-

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

$$\boxed{\sigma = \frac{Q}{tAE} = \frac{ne^2\tau}{m^*}} \ \Omega^{-1}m^{-1}$$

Derivation:

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



Here the force experienced by the electron by external field

$$F = eE \quad — ①$$

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

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

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

$$v_d = a\tau \quad — ②$$

We know that from Newton's II law

$$F = ma \quad — ③$$

By comparing eqns ① & ③

$$eE = ma$$

$$a = \frac{eE}{m} \quad — ④$$

Substituting eqn ④ in eqn ②

$$v_d = \frac{eE\tau}{m} \quad — ⑤$$

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

Then current density interms of 'v_d' is given by

$$J = nev_d \quad — ⑥$$

Substitute eqn ⑤ in eqn ⑥

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

$$J = \frac{ne^2E\tau}{m} \quad — ⑦$$

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

$$J \propto E$$

$$J = \sigma E \quad — ⑧$$

Comparing eqns ⑦ & ⑧ we get

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

$$\boxed{\sigma = \frac{ne^2\tau}{m}} \quad — ⑨$$

Eqn ⑨ is the expression for the electrical conductivity.

Thermal Conductivity:

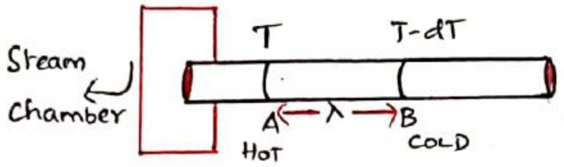
Definition:

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

$$K = \frac{Q}{dT/dx} = \frac{n v^2 k_B \tau}{2}$$

Derivation:-

Consider a unifor metallic rod contain free electron.



Here A & B → Cross-sectional area near hot & cold end

T, T-dT → Temp at A & B.

λ → Mean free path.

The average K.E of electrons crossing A

$$E_1 = \frac{1}{2} m v^2 = \frac{3}{2} k_B T \qquad \text{— ①}$$

III'y K.E of freeelectron at 'B'

$$E_2 = \frac{3}{2} k_B (T-dT) \qquad \text{— ②}$$

Excess energy carried out by electrons from A to B

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

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

$$K.E = \frac{3}{2} k_B dT \qquad \text{— ③}$$

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

$$n = \frac{1}{6} n v \qquad \text{— ④}$$

∴ The excess average energy carried from A to B is given by

$$E = \frac{1}{6} n v \times \frac{3}{2} k_B dT$$

$$E = \frac{1}{4} n v k_B dT \qquad \text{— ⑤}$$

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

$$Q = \frac{1}{4} n v k_B dT - \left[-\frac{1}{4} n v k_B dT\right]$$

$$Q = \frac{1}{2} n v k_B dT \qquad \text{— ⑥}$$

From the definition, we know that

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

$$Q = K \cdot \frac{dT}{\lambda} \qquad \text{— ⑦}$$

By comparing eqn ⑦ & ⑥

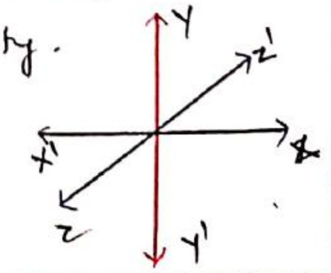
$$K \frac{dT}{\lambda} = \frac{1}{2} n v k_B dT$$

$$K = \frac{1}{2} n v k_B \lambda \qquad \text{— ⑧}$$

wkt $\lambda = \tau v$

$$\therefore \boxed{K = \frac{1}{2} n v^2 k_B \tau} \qquad \text{— ⑨}$$

Eqn ⑨ is the expression for thermal conductivity.



Fermi Distribution function:-

Definition:

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

It is given by

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

Where E → Energy level to be considered.

E_F → Fermi energy level.

k_B → Boltzmann Constant

T → Absolute Temperature.

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

If F(E) = 0, the energy level is vaccant

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

Case (i)

If $E < E_f$ at $T = 0k$

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

$$= \frac{1}{1+e^{(E-E_F)/0}}$$

$$= \frac{1}{1+e^{-\infty}} = \frac{1}{1+0} = 1$$

$$\boxed{F(E) = 1}$$

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

Case (ii)

If T = 0k at $E > E_F$

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

$$= \frac{1}{1+e^{\infty}} = \frac{1}{1+\infty}$$

$$\boxed{F(E) = 0}$$

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

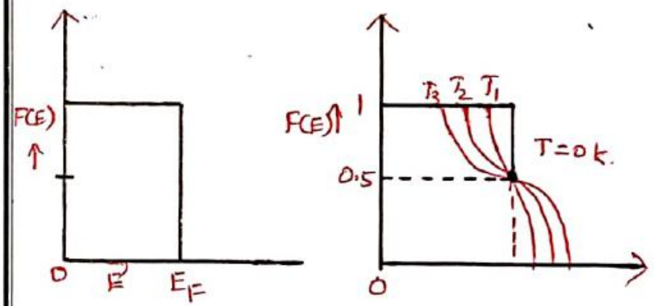
Case (iii)

If T > 0k at $E = E_F$

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

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

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



Variation of E_F with respect to temperature.

When T=0k, occupation is upto E_F

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

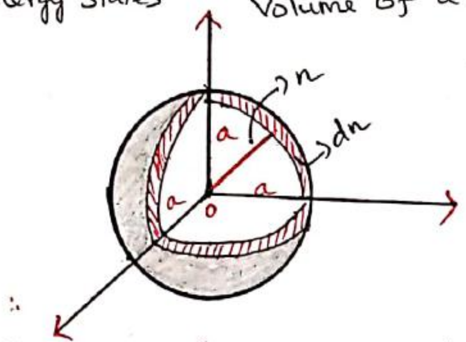
Density of Energy States:-

Definition:

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

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

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



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

- Here n_x, n_y, n_z are the coordinate axes.
- $n \rightarrow$ inner radius of the sphere.
- ~~If~~ E and E+dE are the energy of the inner and outer shell of the sphere.
- The sphere consists of no. of shells, between inner and outer shell each represents a energy level.

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

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

III'ly the energy states within the sphere of radius (n+dn)

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

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

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

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

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

∵ dn very small, neglecting the higher orders,

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

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

We know that

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

$$E = \frac{n^2h^2}{8ma^2} \quad -④$$

Differentiating eqn ④ we have

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

$$(\text{ie})\quad n\,dn = \frac{8ma^2}{2h^2}\cdot dE \quad -⑤$$

From eqn ④

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

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

Hence eqn ③ can be written as

$$N(E)dE = \frac{\pi}{2}\, n.dn \quad — ⑦$$

By substituting eqn ⑤ & ⑥ in ⑦

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

$$\therefore N(E)dE = \frac{\pi}{2}\,\frac{(8m)^{3/2} a^3 E^{1/2} dE}{2h^3} \quad — ⑧$$

Here $a^3 = V \rightarrow$ volume

∴ Density of energy states

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

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

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

According to Pauli's exclusion principle in each state 2 electrons can be accomodated.

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

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

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

Carrier Concentration in Metals:

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

$$n_c = \int Z(E)\, F(E)\, dE \quad — ⑪$$

We know that

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

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

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

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

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

If $F(E)=1$ for energy levels $E=0$ to $E=E_{Fo}$

Then eqn ⑪ becomes

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

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

$$= \frac{4\pi}{h^3}(2m)^{3/2} . \frac{2}{3}\left[E_{Fo}\right]^{3/2}$$

$$\boxed{n_c = \frac{8\pi}{3h^3}(2mE_{Fo})^{3/2}} \quad — ⑬$$

Fermi Energy:-

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

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

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

By raising power on bothsides by 2/3

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

$$\boxed{E_{Fo} = \left[\frac{3n_c}{8\pi}\right]^{2/3}\left[\frac{h^2}{2m}\right]} \quad — ⑭$$

Effective Mass of Electron:-

Definition:-

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

Derivation:-

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

$$v_g = \frac{d\omega}{dk} \quad — ①$$

where $\omega \rightarrow$ angular velocity $(2\pi\nu)$

$k \rightarrow$ wave vector.

we know that

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

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

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

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

$$\omega = \frac{E}{\hbar} \quad — ②$$

∴ Eqn ① can be written as

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

$$v_g = \frac{1}{\hbar}\left[\frac{dE}{dk}\right] \quad — ③$$

Under this condition the acceleration 'a' of an electron

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

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

$$a = \frac{1}{\hbar}\frac{d^2E}{dk^2}\cdot\frac{dk}{dt} \quad — ④$$

The momentum of an electron from de-Broglie wave length

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

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

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

$$p = \hbar k \quad — ⑤$$

Differentiate eqn ⑤ w.r.t. 't'

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

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

Hence eqn ④ can be written as

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

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

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

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

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

$$F = m^*a \quad — ⑧$$

Comparing eqns ⑦ & ⑧

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

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

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

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

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

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

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

Tight Binding Approximation:-

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

Free electron approximation:-

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

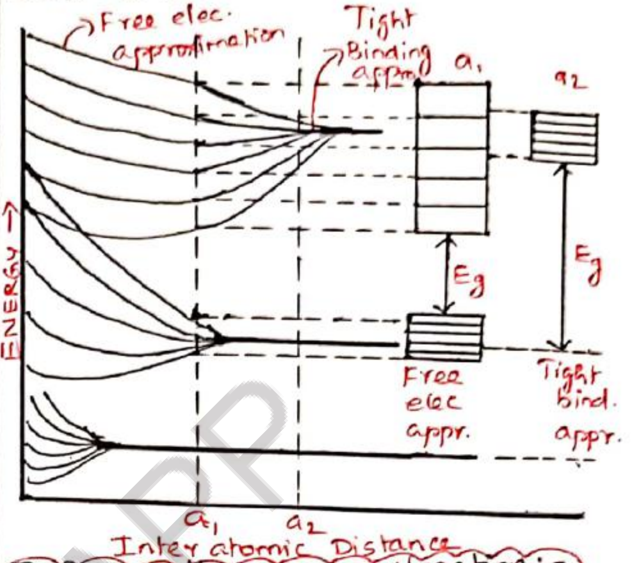
In free electron approximation,

* The P.E of the e^- is assumed to be lesser than its total energy.

* The width of the band gap (E_g) are smaller than the allowed band. (fig)

* The interaction between the neighbouring atoms will be very strong.

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



Tight binding approximation:-

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

In tight binding approximation:

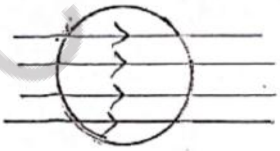
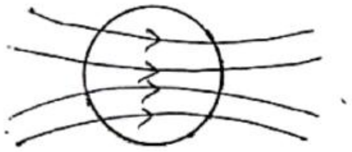
* The P.E of the electrons is nearly equal to the total energy

* The width of the forbidden bands (E_g) are larger than the allowed bands.

* Therefore the interactions between the neighbouring atom will be weak.

* As the atoms are not closer, the inter atomic distance increases and hence the wave functions will not overlap.

Dia, Para, Ferro Magnetic Effects:

Dia	Para	Ferro
(i) It is non-magnetic material consits of no-permanent dipoles	Temporary magnetic material. consits of permanent dipole.	Permanent magnetic material. consits of large no. of permanent dipoles.
(ii) Dipoles are opposite to each other in the absence of external field. Net dipole moment is zero	Dipoles are randomly oriented in the absence of external field. Net dipole moment is minimum.	Dipole are oriented parallel to each other, in the absence of external field. net dipole moment is large.
(iii) In the presence of external field dipole allign opposite to the external field.	In the presence of external field dipoles allign parallel to the external field.	Here also, dipoles allign parallel to the external field.
(iv) Magnetic flux lines are repelled out of the material.	Magnetic flux lines are attracted by the material	Magnetic flux lines are attracted maximum by the material.
$B_{in} \ll B_{out}$ 	$B_{in} \gg B_{out}$ 	$B_{in} >>> B_{out}$ 
(v) Permiability (μ) is less than 1 and susceptibility is -ve $\mu << 1$, $\chi = -ve$	Permiability (μ) is greater than 1 & susceptibility is +ve. $\mu > 1$, $\chi = +ve$	Permiability (μ) is very much greater than 1, susceptibility is +ve, $\mu >> 1$, $\chi = +ve$
(vi) Independent on temperature	Dependent on temperature	Dependent on temperature
(vii) At very low temp. it will be in diamagnetic	Temp above maximum para mag. converted into Dia mag. is known as curie Temp.	Above curie temperature it is converted in to para materials
Ex: Bismuth, Gold.	Ex: Al, Pt.	Ex: Fe, Ni, Co.

Paramagnetism in the Conduction Electrons in metals

According to Langevin's theory the paramagnetic susceptibility is inversely proportional to the temperature.

$$\chi \propto \frac{1}{T}$$

But in some metals susceptibility is independent of temperature.

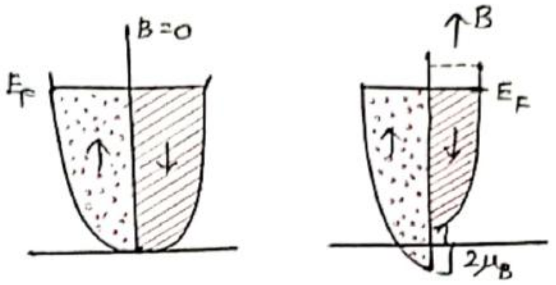
Pauli explains that it's due to the free electrons, can orient only in two directions, either along the magnetic field or against it.

Consider a curve between density of states versus energy at absolute zero of temperature. In this curve there are two parts, one have electron spin along z-direction and another have electron spin opposite to z direction.

In the absence of external field the distribution of electrons in the two parts are equal.

∴ Net mag. moment of the electron gas is zero.

When a mag. field (B) is applied along z-direction, the energy of the spins aligned parallel to B is lowered by the amount μ_B while the energy of the spins opposite to B is raised by the same amount.



As a result, the Fermi level of the two spin distribution shift with respect to each other. And energetically unstable situation.

In order to acquire stable configurations, the e's lying near the Fermi level with antiparallel spins flip into the region of parallel spins until the two Fermi levels become equal again.

No. of electrons which change their direction

$$N_{eff} = \frac{1}{2} Z(E_F) \mu_B B$$

where $Z(E_F) \rightarrow$ Density of states

$\mu_B \rightarrow$ mag. moment of electron.

The factor $1/2$ is due to the fact that the density of states of one spin distribution is half of the total density of the states.

∴ After application of the field

No. of electrons with spin parallel } > No. of electron with spin anti-parallel.

Since each flip increases the magnetisation by $2\mu_B$ (from $-\mu_B$ to $+\mu_B$), the net magnetisation is given by

$$M \approx N_{eff} \times 2\mu_B = Z(E_f)\mu_B^2 B \quad -②$$

The Pauli spin susceptibility of the electron is $B = \mu_0 H$

$$\chi_p = \mu_0 \mu_B^2 Z(E_f) \qquad \chi_p = \frac{M}{H} \quad -③$$

From eqn, we know that χ_p is independent of temp.

From FD distribution we obtain

$$Z(E_F) = \frac{3N}{2E_F}$$

$N \rightarrow$ no. elec per unit volume

$$\therefore ③ \Rightarrow \chi_p = \frac{3\mu_0 N \mu_B^2}{2E_F} = \frac{3\mu_0 N \mu_B^2}{2kT_F}$$

Where $E_F = kT_F$

$$\chi_p = \frac{3}{2}\chi\frac{T}{T_F}$$

Where $\chi = \frac{\mu_0 N \mu_B^2}{kT}$ Classical susceptibility

Since T_F is normally very high, χ_p is smaller than χ by about two orders of magnitude, which is in agreement with experimental results.

Exchange Interaction:

The Weiss theory of ferro-magnetism explains about the molecular field but it is not possible to explain large value of internal field.

To explain the large internal field, Heisenberg gave an explanation which is based on the non magnetic interaction called exchange interaction between electron.

These force appears in the form of spin-spin interaction and strength of the interaction depends upon the interatomic separation. If the interatomic distance is decreased, the electron spin are decreased and the exchange force decreases and become anti parallel spins.

According to Heisenberg theory, the change interaction between the electrons in different quantum states lead to a lower energy provided the spin quantum number of the both states are parallel.

∴ The exchange interaction between the electrons is given by

$$E_{ex} = -2 J_{ij} S_i S_j$$

Where J_{ij} → The exchange integral for the two atoms.

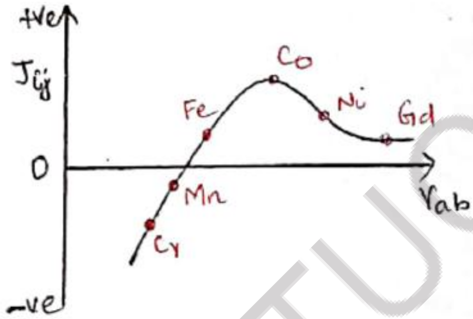
S_i → spin angular moments associated with i^{th} state.

S_j → spin angular moments associated with j^{th} state.

A plot of exchange integral value (J_{ij}) and the interatomic distance (r_{ab})

r_{ab} → interatomic distance.

r_0 → the orbital radius of electron



From graph,

1. The value of J_{ij} is +ve when $\frac{r_{ab}}{r_0} > 3$ (ie) the exchange energy is -ve and hence the parallel orientation is high. Due to this atom possess ferromagnetic properties [Ex; Fe, Co, Ni, Gd]

2. The value of J_{ij} is -ve when $\frac{r_{ab}}{r_0} < 0$ (ie) the exchange energy is +ve and hence the atoms coming under this criteria possess anti-ferromagnetic properties [Ex: Cr, Mn]

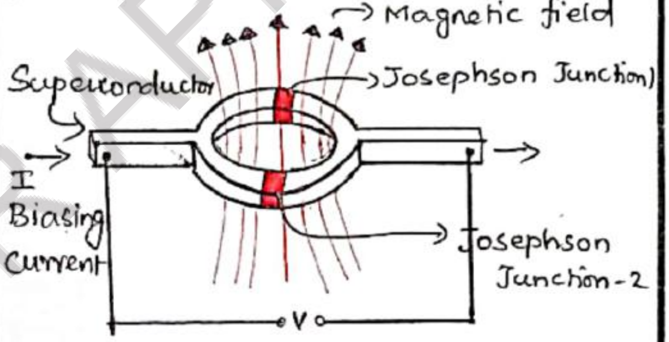
SQUID

SQUID stands for Superconducting Quantum Interference Device. It is an ultrasensitive instrument used to measure very weak magnetic field of the order of 10^{-14} tesla.

Principle:

We know that a small change in magnetic field produces variation in the quantum flux.

Description and Working



A SQUID consists of a superconducting ring which can have magnetic fields of quantum values (1, 2, 3 ...) of flux placed in between two Josephson junctions as shown in figure.

When the magnetic field is applied perpendicular to the plane of the ring, the current is induced at the two Josephson junctions. The induced current produces the interference pattern and it flows arround the ring

So that the magnetic flux in the ring can have the quantum value of magnetic field applied.

Application:

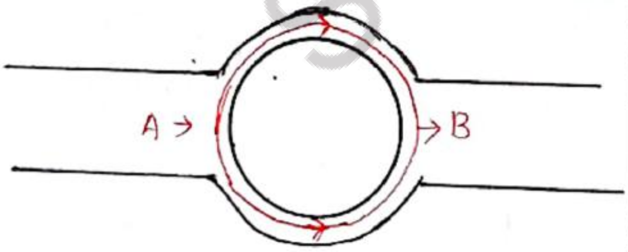
(i) SQUID can be used to detect the variation of very minute magnetic signals in terms of quantum flux.

(ii) It can also be used as storage device for magnetic flux.

(iii) SQUID is useful in the study of earthquakes, removing para-magnetic impurities, detection of magnetic signals from the brain, heart etc.

Quantum Interference Transistor:

Electrons are made to propagate through two arms of the quantum wire ring as shown in the figure.



Suppose an electron wave enters the ring from left to right. The wave entering through 'A' gets split up into two partial waves. A constructive interference can be expected to occur at "B" similar to the optical anlogue as they travel through the same distance.

The constructive interference at the output of the device reduces the resistance of the ring. Various methods of introducing a phase difference of π between the two waves have been sugested. This leads to destructive interference which in turn will increase the resistance by reducing the current.

An external voltage can control the nature of interference and the current. This device is expected to act as a high speed transistor.

GMR Devices – Magnetic Hard Disk Drive with GMR sensor:

GMR sensors, which has a very high magnetic sensitivity are used to read the data at greater speed.

Principle:

In Hard Disk drives, the binary data in terms of zero's (0) and one's (1) are stored by inducing.

magnetic moment in a thin mag- layer and GMR effect is used as the principle to read the data in HDD.

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

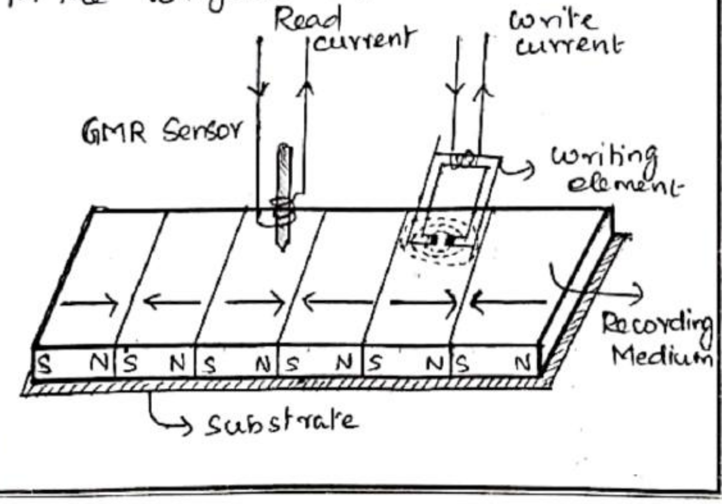
Construction:-

* The HDD consists of recording medium made up of thin layer of magnetic garnets grown over the substrate the GMR sensor.

* The substrate is made up of ferrites and anti ferromagnetic materials. This is used as reading element

* The writing element is made up of inductive magnetic transducer.

* The writing element and the GMR sensor shall be made to slide over the recording media in the longitudinal direction.



Working:- (Writing)

1. Initially the current is passed through the writing element and a magnetic field is induced in between the gap of the inductive magnetic transducer.

2. During writing, the amplitude of current is kept constant, and the direction of current is reversed.

3. Due to reversal of current the reversal of current, the magnetization orientation is reversed in the recording medium (i.e) from south → North

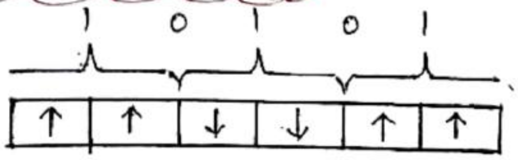
4. When the induced magnetic field is greater than the coercivity of the recording media, then data is recorded in the form of 1.

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

6. When there is no magnetic transition, then it is referred as zero.

7. In this way 0's & 1's are stored in the recording medium

Reading / Retrieving:



1. GMR effect is the principle used to read/retrieve the data

2. When GMR sensor is moving near the recorded medium, then the resistance of GMR sensor varies with respect to orientation of the magnetic moments. as follows.

* When the layer are magnetised in parallel manner then the resistance is minimum, therefore maximum current flows. This is represents. ~~the~~ the data as One (1)

* When the layers are magnetised in antiparallel manner, then the resistance is maximum, therefore minimum (no current) current flows This is represents the data as Zero (0)

3. Therefore, with the help of the reading current, the Zero's (0's) and one's (1's) can be retrieved from the magnetic hard disc.

Advantages:

* Very large storage capacity.

* Compact in size.

* Non diffusive & very senstive in reading.

Disadvantages

* HDD is slower than SSD

* Consume more power

* Data may be corrupted, due to thermal radiation.

Carrier Concentration - Instrinsic Semiconductor:-

- Elemental
- Indirect

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

Derivation:

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

$$n = p = n_i$$

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

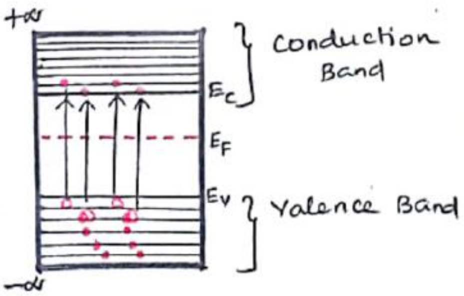
$$\int dn = n = \int_{E_c}^{\infty} Z(E)\, F(E)\, dE \quad —①$$

We know that, Density of energy states

$$Z(E)dE = \frac{4\pi}{h^3}(2m_e^*)^{3/2} E^{1/2}\, dE \quad —②$$

Probability of Electron occupation

$$F(E) = \frac{1}{1+e^{\frac{(E-E_F)}{k_BT}}} \quad —③$$



$$\therefore n = \int_{E_c}^{+\infty} \frac{4\pi}{h^3}(2m_e^*)^{3/2} E^{1/2} \frac{1}{1+e^{\frac{(E-E_f)}{k_BT}}}\, dE$$

$$—④$$

Here

m_e^* - Effective mass of Electron.

E - KE of conduction electron

$$E = E - E_c$$

E_c - Lower conduction Energy level.

Eqn ④ can be written

$$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2} \int_{E_c}^{+\infty} \frac{(E-E_c)^{1/2}}{1+e^{\left(\frac{E-E_c}{k_BT}\right)}}\, dE \quad —⑤$$

We know that at T>0K

$$E - E_f >> k_BT$$

$$\frac{E-E_f}{k_BT} >> 1 \quad (or) \quad e^{\left(\frac{E-E_f}{k_BT}\right)} >> 1$$

$$\therefore 1 + e^{\frac{(E-E_f)}{k_BT}} \simeq e^{\frac{(E-E_f)}{k_BT}}$$

Hence eqn ⑤ can be written as

$$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2} \int_{E_c}^{\infty} \frac{(E-E_c)^{1/2}}{e^{\left(\frac{E-E_f}{k_BT}\right)}}\, dE$$

$$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2} \int_{E_c}^{\infty} (E-E_c)^{1/2} e^{E_f - E/k_BT}\, dE$$

$$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2} e^{E_F/k_BT} \int_{E_c}^{\infty} (E-E_c)^{1/2} e^{-E/k_BT}\, dE \quad —⑥$$

To calculate eqn ⑥

Let	when	
$E - E_c = x$	$E = E_c$	$E = \infty$
$E = x + E_c$	$E_c - E_c = x$	$\infty - E_c = x$
$dE = dx$	$x = 0$	$x = \infty$.

∴ Eqn ⑥ can be written as

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

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

Using gamma function

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

Hence

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

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

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

Density of Holes (P) :-

It is given by

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

Here

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

here

$m = m_h^*$

$E = E_v - E.$

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

By substituting and simplyfying the density of holes

$$\boxed{P = 2\left[\frac{2\pi m_h^* k_BT}{h^2}\right] e^{\frac{(E_v-E_f)}{k_BT}}} \quad ⑩$$

Expression for intrinsic carrier concentration.

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

$n = p = n_i$ —⑪

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

Hence $n_i^2 = n \times p$ given by ⑫

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

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

$$\boxed{n_i = 2\left(\frac{2\pi k_BT}{h^2}\right)^{3/2}(m_e^* m_h^*)^{3/4} e^{-E_g/2k_BT}} \quad ⑬$$

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

Density of Holes:-

It is given by

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

Here

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

Here $m = m_h^*$

$$E = E_v - E$$

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

Eqn ①

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

$$P = \frac{4\pi}{h^3}(2m_h^*)^{3/2} e^{-E_f/k_BT} \int_{-\infty}^{E_v} (E_v - E)^{1/2} e^{E/k_BT}\, dE \quad \text{—②}$$

Let

$E_v - E = x$

$E = E_v - x$

$dE = -dx$

when

$E = -\infty$

$E_v - (-\infty) = x$

$E_v + \infty = x$

$\boxed{x = \infty}$

when

$E = E_v$

$E_v - E_v = x$

$\boxed{x = 0}$

Eqn ② becomes

$$P = \frac{4\pi}{h^3}(2m_h^*)^{3/2} e^{(-E_f/k_BT)} \int_{\infty}^{0} x^{1/2} e^{\frac{(E_v - x)}{k_BT}} (-dx)$$

$$P = \frac{4\pi}{h^3}(2m_h^*)^{3/2} e^{\frac{E_v - E_f}{k_BT}} \int_{0}^{\infty} x^{1/2} e^{-x/k_BT}\, dx$$

Using Gamma function

$$\int_0^{\infty} x^{1/2} e^{-x/k_BT}\, dx = \frac{\sqrt{\pi}}{2}\left[k_BT\right]^{3/2}$$

Hence

$$P = \frac{4\pi}{h^3}\left[2m_h^*\right]^{3/2} e^{\frac{E_v - E_f}{k_BT}} \frac{\pi^{1/2}}{2} (k_BT)^{3/2}$$

$$\boxed{P = 2\left[\frac{2\pi m_h^* k_BT}{h^2}\right]^{3/2} e^{\frac{(E_v - E_f)}{k_BT}}}$$

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

Extrinsic Semi Conductor

Def:

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

Types:

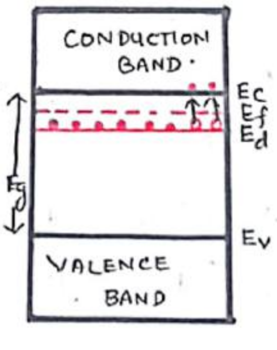
These are classified into two types based on the type of impurity

(i) n type (penta valent impurity)

(ii) p type (Trivalent impurity)

Carrier Concentration - n type Semiconductor

* The energy level diagram is shown in the figure.



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

WKT the density of electrons in the conduction band

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

m_e^* → Effective mass

k_B → Boltzmann Constant

No. of holes (or) donors $= N_d\,[1 - F(E_d)]$ ②

$F(E_d)$ – Probability of Electron in donar energy level.

$1 - F(E_d)$ – Probability of ionized donars

N_d – Total no. of donar atoms per unit volume.

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

∴ Eqn ②

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

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

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

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

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

∴ The above eqn can be written as

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

At equilibrium

Density of Electron in the conduction Band (n) } = Density of holes in the Donor energy level (n_h)

$\therefore n = n_h$

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

By Rearranging the above eqn

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

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

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

Taking log on bothsides

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

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

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

$$\boxed{E_f = \frac{E_c + E_d}{2} + \frac{k_B T}{2}\log\left[\frac{N_d}{2\left[\frac{2\pi m_e^* k_B T}{h^2}\right]^{3/2}}\right]} \quad ④$$

Carrier Concentration:-

By substituting eqn ④ in eqn① we have

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

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

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

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

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

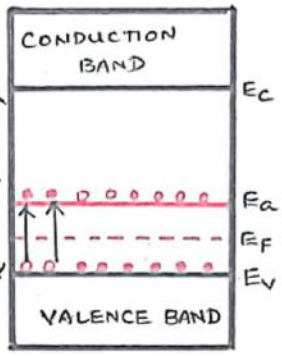
$$\boxed{n = \left[2 N_d\right]^{1/2}\left[\frac{2\pi m_e^* k_B T}{h^2}\right]^{3/4} e^{\left[\frac{E_d-E_c}{2k_B T}\right]}} \quad \text{—⑥}$$

Eqn ⑥ is the expression for Carrier concentration of n-type Semi conductor, ~~in terms~~

P-Type Semiconductor:

* The Energy level diagram is shown in the figure

* Here the excess no. of holes from a new energy Level (E_a) acceptor level just below the conduction Band.



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

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

E_v → Top energy level of valence Band

E_a → Acceptor Energy level

E_f → Fermi Energy level.

Density of Electrons in the acceptor energy level is given by

$$n = N_a\left[F(E_a)\right]$$

$$n_e = N_a \frac{1}{1+e^{\frac{(E_a-E_f)}{k_B T}}} \quad \text{—②}$$

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

$$\therefore \quad 1+e^{(E_a-E_f)/k_B T} \simeq e^{(E_a-E_f)/k_B T}$$

$$\therefore \quad n_e = N_a\, e^{\frac{(E_f-E_a)}{k_B T}} \quad \text{—③}$$

At equilibrium,

$$\left.\begin{array}{l}\text{No., electrons in} \\ \text{the acceptor} \\ \text{energy level (p)}\end{array}\right\} = \begin{array}{l}\text{No of holes in} \\ \text{Valence band}(n_e)\end{array}$$

$$2\left[\frac{2\pi m_h^* k_B T}{h^2}\right]^{3/2} e^{\frac{(E_v-E_f)}{k_B T}} = N_a\, e^{\frac{(E_f-E_a)}{k_B T}} \quad \text{—④}$$

$$\frac{e^{\left(\frac{E_v - E_f}{k_BT}\right)}}{e^{\left(\frac{E_f - E_a}{k_BT}\right)}} = \frac{N_a}{2\left[\frac{2\pi m_h^* k_BT}{h^2}\right]^{3/2}}$$

$$e^{\left[\frac{E_v - E_f - E_f + E_a}{k_BT}\right]} = \frac{N_a}{2\left[\frac{2\pi m_h^* k_BT}{h^2}\right]^{3/2}}$$

$$e^{\left[\frac{-2E_f + E_v + E_a}{k_BT}\right]} = \frac{N_a}{2\left[\frac{2\pi m_h^* k_BT}{h^2}\right]^{3/2}}$$

Taking log on bothsides,

$$\frac{-2E_f + E_v + E_a}{k_BT} = \log \frac{N_a}{2\left[\frac{2\pi m_h^* k_BT}{h^2}\right]^{3/2}}$$

Rearranging Equation,

$$\boxed{E_f = \frac{E_a + E_v}{2} - \frac{k_BT}{2}\log\left[\frac{N_a}{2\left[\frac{2\pi m_h^* k_BT}{h^2}\right]^{3/2}}\right]} \quad —⑥$$

The density of holes in the p type can be written by substituting equation ⑥ in eqn ①

$$P = 2\left[\frac{2\pi m_h^* k_BT}{h^2}\right]^{3/2} e^{\left[\frac{E_v - E_f}{k_BT}\right]}$$

Here $e^{\left[\frac{E_v - E_f}{k_BT}\right]}$ can be rearranged as follows,

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

$$= \exp\left[\frac{2E_v - E_a - E_v}{2k_BT} + \frac{1}{2}\log\left[\frac{N_a}{2\left[\frac{2\pi m_h^* k_BT}{h^2}\right]^{3/2}}\right]\right]$$

$$= \exp\left[\frac{E_v - E_a}{2k_BT} + \frac{1}{2}\log\frac{N_a}{2\left[\frac{2\pi m_h^* k_BT}{h^2}\right]^{3/2}}\right]$$

∴ Eqn ① can be written as

$$p = 2\left[\frac{2\pi m_h^* k_BT}{h^2}\right]^{3/2} \exp\left[\frac{E_v - E_a}{2k_BT} + \frac{1}{2}\log\frac{N_a}{2\left[\frac{2\pi m_h^* k_BT}{h^2}\right]^{3/2}}\right]$$

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

$$\boxed{p = (2N_a)^{1/2}\left(\frac{2\pi m_h^* k_BT}{h^2}\right)^{3/4} e^{(E_v - E_a)/k_BT}} \quad —⑦$$

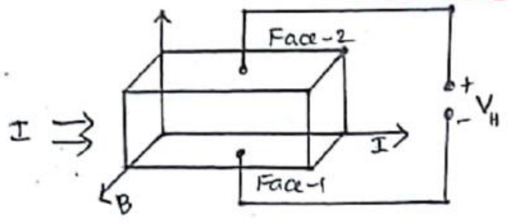
Eqn ⑦ is the expression for the carrier concentration of 'p'-type semiconductor.

Hall Effect:-

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

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

Hall Effect in n-type Semiconductor & P-type



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

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

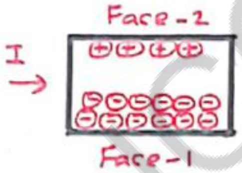
Force due to magnetic field (Downward) } $= Bev$ —①

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

At equilibrium ① = ②

$$Bev = eE_H$$

$$E_H = Bv \quad —③$$



we know that

Current density

$$J_x = -nev$$

$$v = \frac{-J_x}{ne} \quad —④$$

Substitute eqn ④ in eqn ③

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

$$E_H = R_H J_x B \quad —⑤$$

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

-ve sign indicates Elec. field in -ve Y axis

∴ Hall coefficient

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

|||'y in P-type semiconductor Current flow due to flow of holes (+ve charge)

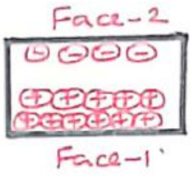
Compare with n-type semiconductor current density $J_x = pev$

$$v = \frac{J_x}{pe} \quad —⑥$$

Substitute eqn ⑥ in ③

$$E_H = R_H J_x B \quad —⑦$$

$$\boxed{R_H = \frac{1}{pe}}$$



Hall coefficient interms of Hall voltage

Hall voltage $V_H = E_H t$ —⑧

where E_H → Hall field.

Substitute eqn ⑦ in eqn ⑧.

$$V_H = R_H J_x B t \quad —⑨$$

Area of the sample A = thickness × Breadth

$$A = bt$$

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

$$J_x = \frac{I_x}{bt} \quad —⑩$$

Substitute eqn ⑩ in eqn ⑨

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

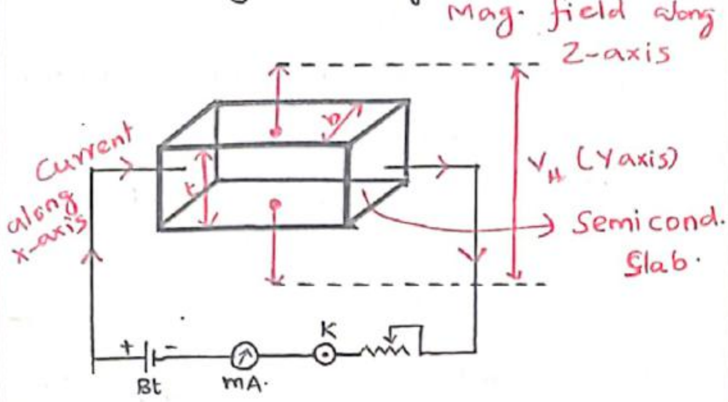
$$V_H = \frac{R_H I_x B}{b}. \quad —⑪$$

$$\boxed{R_H = \frac{V_H b}{R_H B}} \quad —⑫$$

Eqn ⑫ gives hall coefficient i.e. interms of hall voltage.

Experimental Determination of Hall Co efficient

A semiconductor Slab of thickness 't' and breadth 'b' is taken and current is passed through x-axis using battery.



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

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

$$\boxed{R_H = \frac{V_H b}{I_x B}}$$

Mobility of charge Carriers:

We know that, Hall coefficient

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

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

For n-type semiconductor

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

$$ne = \frac{-1.18}{R_H} \quad ①$$

For p-type semi conductor

$$R_H = \frac{1.18}{pe} \qquad pe = \frac{1.18}{R_H} \quad ②$$

Electrical conductivity

for n-type semiconductor

$$\sigma_e = n e \mu_e \quad ③$$

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

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

For p-type semicond.

$$\sigma_h = p e \mu_h \quad ⑤$$

$$② \Rightarrow \mu_h = \frac{\sigma_h}{\frac{1.18}{R_H}}$$

$$\mu_h = \frac{\sigma_h R_H}{1.18} \quad ⑥$$

Application of Hall Effect:-

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

(ii) Used to find the carrier concentration

$$n = \frac{1}{eR_H}$$

(iii) Used to find the mobility of charge carriers

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

Schottky Diode:-

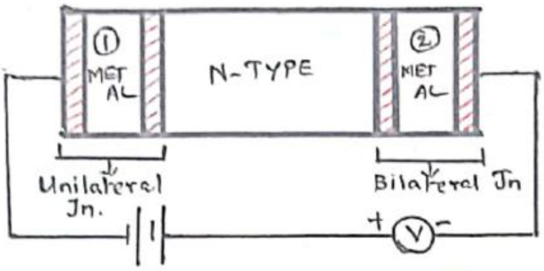
Schottky diode is a unilateral device, in which current flow from metal to semiconductor in one direction.

Construction:-

A Schottky diode also called as Schottky barrier diode. It is made up of 2 juctions.

(i) Unilateral [Metal-Semiconductor]

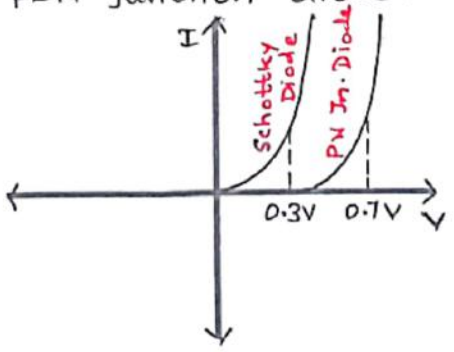
(ii) Bilateral [Metal-Semiconductor]



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

Working:

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



As per V-I curve, during forward bias for a Schottky diode I increase enormosly even for small applied V, due to 3 component of current occurs in schottky diode

Application:

* Due to low voltage drop, they are used in high switching system

* They are used in BJT

* It is used is Radio frequency application.

* It is used in high power supply

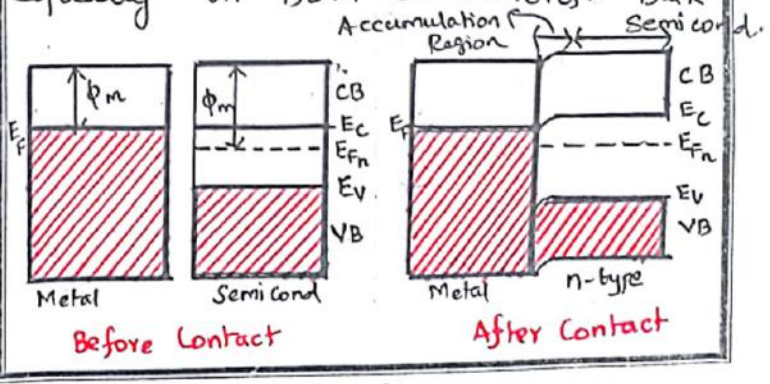
Ohmic Contacts:

Definition:

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

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

Here like current is conducted equally in both directions.



Before Contact After Contact

Working:

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

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

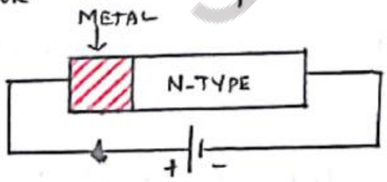
∴ An accumulation region near the interface is appeared. (Semi-conductor side)

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

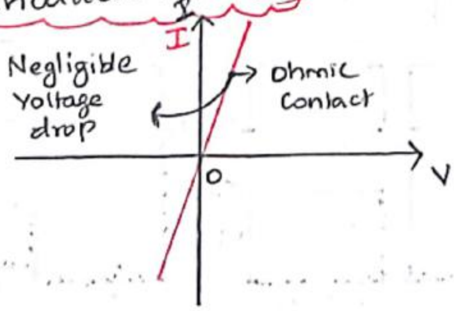
Accumulation region has a higher conductivity than the bulk semiconductor due to higher concentration.

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

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



V-I characteristics:



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

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

Applications:

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

OPTOELECTRONICS DEVICE - LIGHT DECTORS:

* Opto electronic devices such as light dectors (or) photo dectors are the devices which convert the light signal into electrical signals.

* The Three main photo detecters used in optical fiber communication system are

(i) P-i-n-Photo diode (PIN Diode)
(ii) Avalanche Photo diode (APD)
(iii) PN junction photo dector

→ P-i-n-Photo Diode (PIN Diode)

* Principle:

- This Diode works in Reverse bias. Under reverse bias, light is made to fall on neutral region.

- Electron hole pairs are generated and accelerated by the external electric field, which results in photo-current.

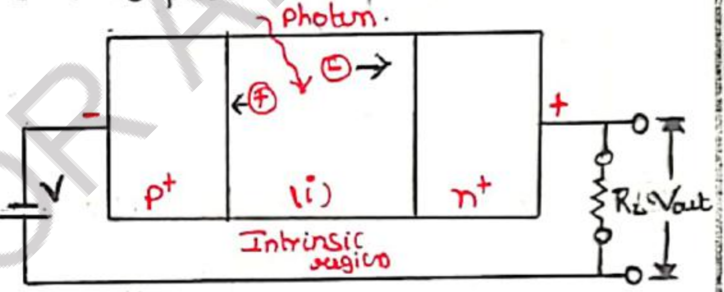
* Construction:

- It consists of three region p, i and n.

- The p-n regions are madeup of semiconductor material [silicon, germanium].

- The intrinsic region is a neutral, where it is at the centre of the p-type and n-type region and it is lightly doped with n-material.

- Since the p-n region is seperated by an intrinsic region (i), it is called as positive-intrinsic-negative (P-i-n) photo diode.



Working:

* The PIN Diode is given very high reverse bias to attract the charge carriers from the intrinsic region.

* The photon incident on the intrinsic region produces electron-hole pair, by the transfer of electrons from Valence band to Conduction band, leaving a hole.

* The movement of electrons in the conduction band creates flow of charges. Hence light energy is converted into electrical energy.

Solar Cell:

* Principle:

A solar cell is basically a P-N junction photo diode, which converts solar energy (light energy) into electrical energy. With larger efficiency of photon absorption.

* The symbol of the solar cell

* Construction:

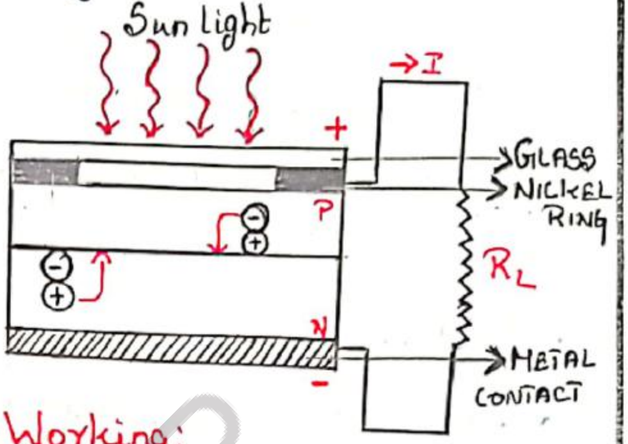
◎ A solar cell is made up of a heavily doped 'p' and "n" type material.

◎ The P-N diode is packed in a can with glass window on top such that light may fall upon P and N type material.

◎ The thickness of the p-region and n-region is very small. Therefore charge carriers generated in this region can easily diffuse to the junction.

◎ Nickel ring at the top and metal at bottom act as terminals.

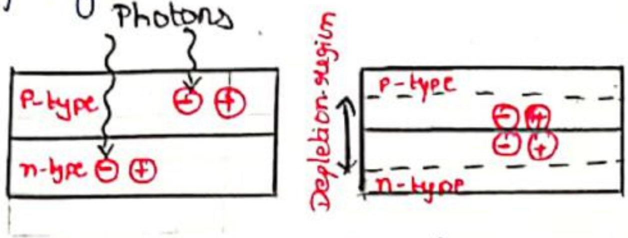
◎ The two terminals connected to the load resistance R_L through the ohmic contacts.



* Working:

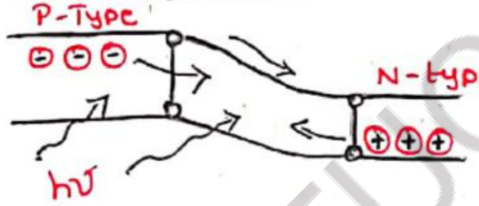
- Light radiation is allowed to fall on P-N junction diode, without load resistence (R_L).
- The photon energy is sufficient to break the covalent bond and produce electron-hole pair.
- These electrons and holes quickly diffuses and reaches the depletion region.
- Therefore the strong barrier electric field existing in the junction
- The minority carrier electrons in the p-side cross the barrier potential to reach N-side and the holes in N-side move to the p-side.

- The minority current is directly proportional to the illumination of light.



- The electrons and holes accumulate on either side of the junction, which gives rise to open-circuit voltage (V_0).
- Load Resistance R_L is connected across the diode, reverse current I_R flows through the circuit.

Energy level Diagram



* Merits:

- utilize renewable energy.
- Eco-friendly
- pollution free
- Life time durability high.

* Demerits:

- Cost is very high.
- seasonal energy
- Occupies more energy.

* Uses:

- power production.
- used in artifical satellite and space probes.

LIGHT EMITTING DIODE (LED).

* Definition:

- LED is a semiconductor P-n junction diode which converts electrical energy to light energy under forward biasing.

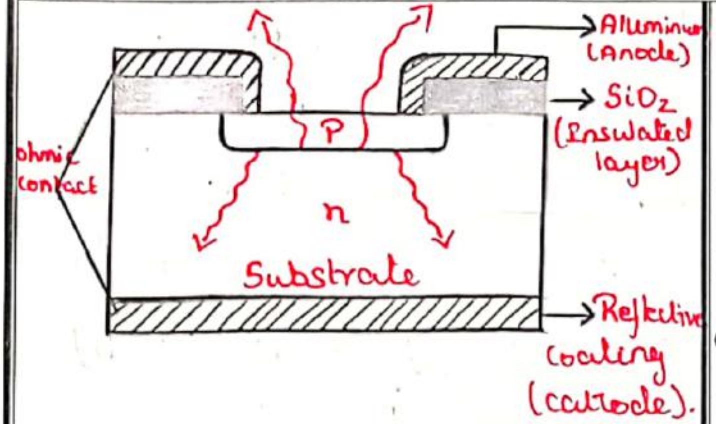
Symbol.

* Principle:

- Injection Luminescence is the principle used in LED's.
- The injection of electrons into the p-region from n-region makes a direct transition from conduction band to valence band. The electrons recombines with holes and emits photons of energy Eg

* Construction:

- The p-n junction is formed by diffusion techniques by doping silicon with GaAS crystal.
- Where, n-type is grown on a substrate and a p-type layer is deposited on it by diffusion.



- To increase the radiative recombination, the thickness of n-layer is higher than the thickness of 'P' layer.

- Ohmic contacts are made by aluminium in such a way that top layer "p" material is left uncovered for the emission of light, where the carrier recombination takes place.

* Working:

- Under forward biasing, Majority charge carriers of n-type (electrons) moves to p-type as minority carriers

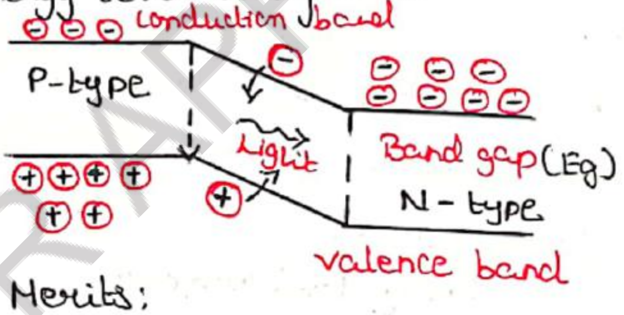
- similarly, majority charge carriers of p-type (holes) moves to n-type as minority carriers

- By this process, excess of minority carriers are injected in both p and n region, This is called minority carrier injection.

- Biasing Voltage is further increased, excess minority holes carriers diffuse away from the junction and directly recombine with the majority carriers.

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

Energy level diagram:



* Merits:

- Very fast Response.
- Cost is very low.
- Smaller in size.
- Long life time.

* Demerits:

- power output is low
- Less Directional.
- Intensity is lesser than Lasers.

* Applications:

- Used in display devices.
- Used in pilot light.
- Used in indicator lamp.
- IR LEDS used in wire-less communication.

LASER DIODE:

* Definition:

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

* Principle:

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

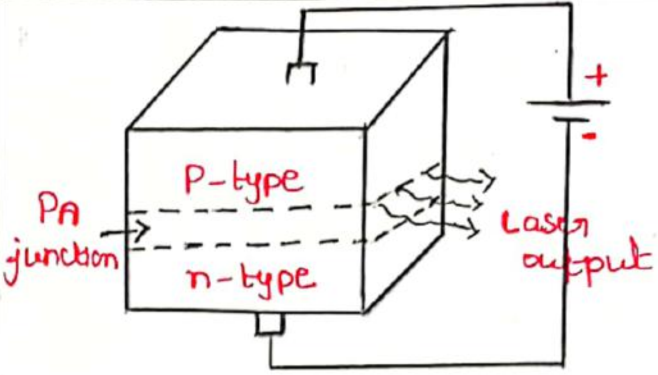
* Construction:

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

⊙ The crystal is cut in the form of platelet (0.5mm-thickness) Consists of two regions n-type & p-type.

⊙ Metal electrodes are connected to both upper & lower surfaces of the S.C diode.

⊙ Forward bias voltage is applied through metal electrodes.



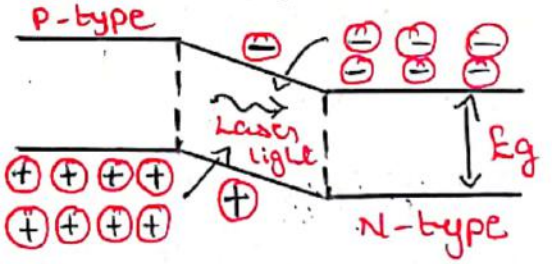
⊙ The photon emission is stimulated in a very thin layer of pn junction.

⊙ The end faces of the Pn junction are well polished and parallel to each other.

⊙ It acts as an optical resonator through which the emitted light comes out.

* Working:

⊙ When the pn-junction is forward biased.



⊙ Electrons & holes are injected into junction region.

⊙ The region around junction contains a large number of electrons in the conduction band and holes in Valence band

- During recombination, light photons are produced.
- During forward bias voltage is increased, more photons are emitted.
- These photons trigger a chain of stimulated recombinations more photons in phase travel forth & back ~~of~~ by two polished surfaces of junction.
- After gaining enough strength Laser beam of wavelength 8400 Å is emitted from the junction. $E_g = hc/\lambda$.

* Merits:

- Compact in size.
- High efficiency..
- Less power consumption.
- Waveform is continuous/pulsed.

*Demirts:

- Output has large divergence
- poor coherence & Mono-chromaticity

* Applications of laser diodes:

- Used in optical communication.
- Used in Barcode readers.
- Used in printing industry.
- Used as writing head in Disc drives.
- Used in various Industry applications such as cladding welding etc.

OLED – Organic LED:

* Definition:

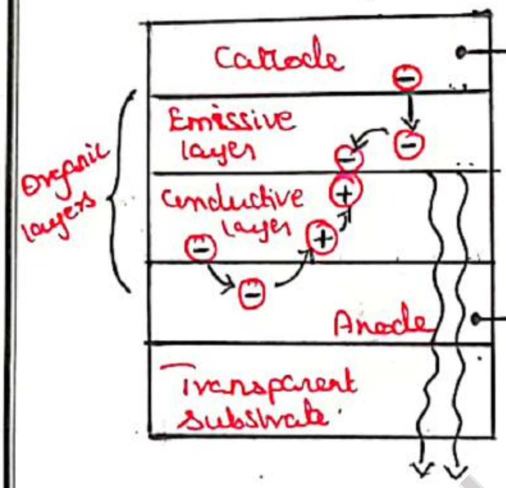
- OLED are solid state devices made up of thin films of organic molecules that produce light with the application of electricity
- It is also known as light emitting polymers (LEP) or Organic electro luminescence
- Thickness of these layers is around 100 - 500 nm thick.

* Principle:

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

* Construction:

◎ It is constructed with different layers of polymers coated with Organic compound.



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

◎ This whole layers placed over transparent electrode layers.

* Working:

◎ Forward bias voltage is applied across the OLED

◎ Due to this cathode diffuse electron into emissive layer.

◎ Anode gets an electron from Conductive layer & produces a hole in conductive layer.

◎ Thus, emissive layer becomes rich in negative charged particles & conductive layer becomes rich in positive charged particles.

◎ Due to the electrostatic force, electrons and holes, come closer & recombine with each other.

◎ In organic sc, holes moves faster than electrons.

◎ This recombination produces light and it is emitted through the transparent substrate.

* Merits:

- It is thin & flexible.
- Light weight
- Larger field View
- Emission is brighter than normal light (LED'S).

* Demerits:

- Manufacturing cost is high.
- Easily damaged.
- Maintainence is high.

* Application:

- Used in cell phones, car radios, digital camera.
- Used in TV screens, Computers displays, adverti -sing
- Automative dash boards.
- Used in flexible display boards.

ELECTRO-OPTIC MODULATORS :

*Electro-Optic Effect:

The phenomenon in which the optical properties of a material change in response to a varying electrical field is known as electro-optic effect and the Crystals with special optical properties that allow an electrical signal to control and modulate a beam of light are known as Electro-optic modulators.

Types of electro-optic modulators

Base on type of the modulated beam, electro-optic modulators are classified as

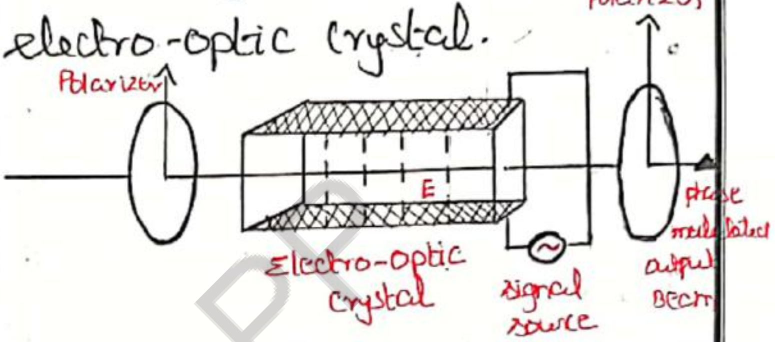
* Intensity modulator.
* phase modulator
* Amplitude modulator
* Polarization modulator.

*Principle:

Electro-optic modulators consists of a non-linear Crystal [lithium niobate]. The refractive index varies with strength of the applied electric field. Based on the linear electro-optic effect.

* Operation:

* A voltage applied across the electro-optic crystal.



* Due to plane-polarized light propagating through the crystal to resolved into two components.

* The change in retardation between two components is proportional to the magnitude of the electric field.

* A crossed polarizer analyzes the output beam, resulting in intensity modulation.

*Significance:

- Modify the properties of a travelling light wave.

* Application:

- Communications.
- Information processing.
- Digital signal processing.

* Properties of electro-optic material:
  - Large change in refractive index per volt.
  - High optical quality and transmission.
  - Low dielectric constant.

PLASMONICS:

* Plasmon:

Plasmon is a collective wave where billions of electrons oscillate in synchronization.

* Plasmonics:

Plasmonics refers to the resonant interaction between electromagnetic radiation and free electrons at the interface between a metal and a dielectric material.

* Principle:

Surface Plasmon Resonance

High intense photons and free electron interaction causes generation of density electron waves called surface plasmons.

* Conduction electrons on the nanoparticle surface of the plasmonic material undergo a collective oscillation when excited by light at specific wavelengths.

* This oscillation, which is known as surface plasmon resonance (SPR).

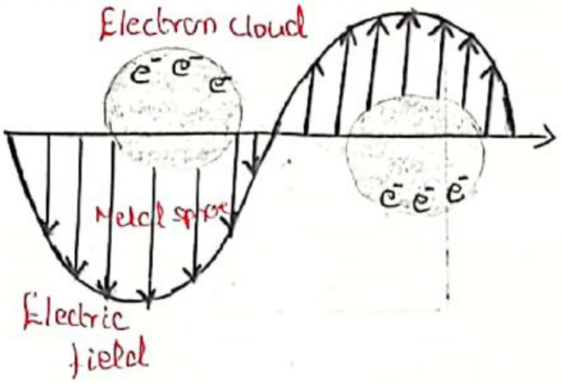
*Theory:

* The plasmon resonance of the free electrons in the metal nanoparticle, studied by polarizability.

* When an excitation occurs, the electrons will oscillate by external electric field.

* On metal's surface, electrons will make each other to oscillate. After excitation waves will appear [longitudinal & damping]

* Surface plasmons polaritons resonance, controlled by size.



and optical properties of nano-particle composition and medium in which the particles are embedded.

* Application:

* Superfast optical computers

* Tumor killing cancer therapies

* Laser for self-driving cars.

Switching Devices

The opto-electronic switching devices are very useful for computing and light activated logic gates applications.

* Definition:

Switching refers to a phenomenon in which transmission of an optical field through a device is switched among two or more possible states by optical means.

* Types of Optical switching:

There are two types of optical switching.

* P-i-n [Multi Quantum Well]

- Self electro optic effect (SEED) device.

* The Quantum Controlled Stark Effect [QCSE]

* Self Electro Optic Effect: [SEED]

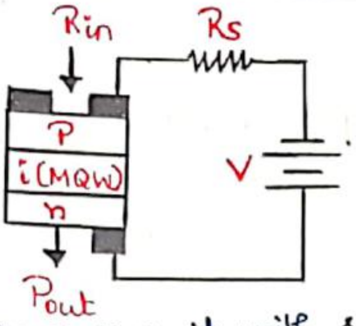
* Principle:

The photocurrent flowing through the current including series resistor, changes the voltage across the modulator, this influences its absorption and transmission.

* Circuit:

* In p-i (MQW)-n diode, by the reverse bias voltage, the tunneling current varies.

* The photocurrent - bias voltage exhibits Negative differential resistance (NDR).



- SEED circuit with series resistor
- P_{in} → incident optical power

$P_{out} = I^2 R_S$ is electric output power.

- I is the photo current flowing through resistance (R_S)

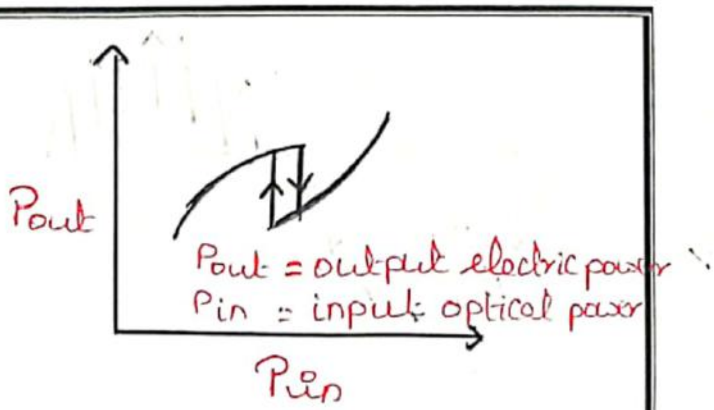
* Operation

* The photo current increases due to recombination of electrons and holes [tunneling of charge carriers]

* The negative bias across the diode decreases. The heavy hole absorption peak is shifted to higher energies.

* Voltage drops $I^2 R_S$ across the series resistor increases.

* When the photo current decreases and correspondingly output electric power decreased.



* Increase of input optical power increases the output electric power due to ordinary photon absorption by the diode.

* Photonic switching can also illustrated with two beams, one for transmission and one for control.

ZENER - BLOCH OSCILLATIONS:-

It denotes the oscillation of a particle (electron) confined in a periodic potential when a constant force is acting on it.

Derivation:-

for 1-D equation of motion for an electron in constant electric field E.

$$F = \frac{dP}{dt} = -eE \longrightarrow ①$$

$$P = h/\lambda$$

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

$$P = \hbar k. \longrightarrow ②$$

$$\therefore ① \Rightarrow \frac{d(\hbar k)}{dt} = -eE$$

$$\frac{dk}{dt} = \frac{-eE}{\hbar} \longrightarrow ③$$

Integrate the eqn. ③

$$k(t) = k(0) - \frac{eE}{\hbar}t$$

W.k.T.

Velocity of the electron is "v"

$$V(k) = \frac{1}{\hbar}\frac{d\mathcal{E}}{dk}.$$

where $\mathcal{E} \Rightarrow$ Energy band

$$\mathcal{E}(k) = A\cos ak.$$

where a => lattice

A => Constant

$$V(k) = \frac{1}{\hbar}\frac{d(A\cos ak)}{dk}$$

$$V(k) = -\frac{Aa}{\hbar}\sin ak.$$

The electron position 'x' is

$$x(t) = \int_0^t -\frac{Aa}{\hbar}\sin ak\, dt$$

$$\boxed{x(t) = -\frac{A}{eE}\cos\left(\frac{aeE}{\hbar}t\right)}$$

$\therefore$ Angular frequency of oscillation $\Big\}$ $\omega_B = \frac{aeE}{\hbar}$

RESONANT TUNNELING:

Transmission probability of the double symmetric barrier is maximum and hence, the tunneling current reaches peak value when energy of electron wave is equal to quantised energy state of the well.

COULOMB - BLOCKADE EFFECT:

The charging effect which ~~book~~ block the injection or rejection of a single charge into or from a quantum dot is called "Coulomb Blockade Effect"

SEMICONDUCTOR PHOTONIC STRUCTURE :-

Photonic structure that are made up of semiconducting material are called semiconductor photonic structure.

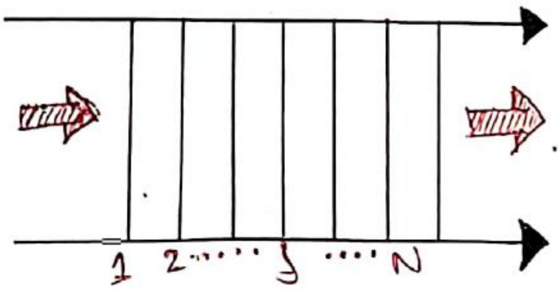
Photonic structure are building block for many optical application in which, light manipulation is required in optical filtering. lasing, light emitting diode and photovoltaics.

They have three dimensional periodic structure, 1D, 2D, and 3D photonic crystal.

There are '3' type of photonic crystal.

i) 1D - Photonic crystal
ii) 2D - Photonic Crystal
iii) 3D - Photonic Crystal

i) 1-D Photonic Crystal :-



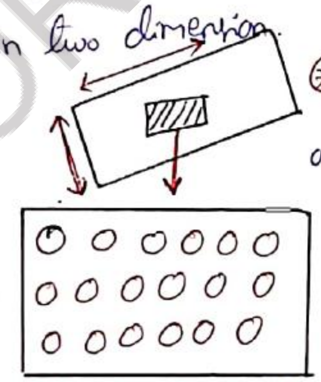
A photonic crystal is a one-dimensional virtual medium, whose refractive index has periodic modulation.

Thin film layer of material of different dielectric constant are periodically deposited.

A 'Bragg Grating' is an example for this type of photonic crystal.

ii) 2D - Photonic Crystal :-

A 2D photonic crystal is a two-dimensional virtual medium whose refractive index is periodically modulated in two dimension.



C.S of 2D Crystal.

* The Haley fiber or photonic crystal fiber are example for 2D - photonic crystal.

* A Dielectric material dug with a periodic lattice containing deep and parallel cylindrical holes are formed.

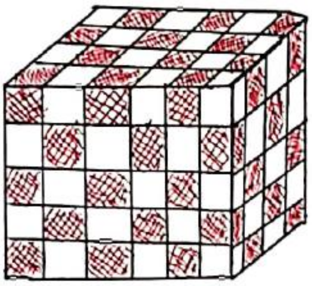
* The wave propagation is being considered along direction normal to the holes.

iii) 3D – Photonic Crystal :-

The dielectric Constant is made to vary periodically in 3D dimensions.

In this photonic crystal, photonic bandgap prohibits electromagnetic propagation.

This photonic crystal is the efficient fabrication of lage-dimention crystal with high refractive index variation.



3 D.

OPTOELECTRONIC DEVICES :-

Optics and electronics together form a new branch of study called as optoelectronics, which include the design and manufacture of a hardware device that converts electrical energy into light energy and vice-verse through semiconductor.

There are two type of optoelectronic device.

i) Active optoelectronic Device
ii) Passive optoelectronic Device

i) Active Device :-

The light intensity can be directly varied in accordance with applied input voltage source the external light is not needed for the working.

eg: i) LED
ii) Laser Diode

ii) Passive Device :-

The light intensity is not changed by controlling voltage. On the other hand, the plane of polarisation is turned by the application of control voltage.

eg. Kerr Cell
NLO Crystal.

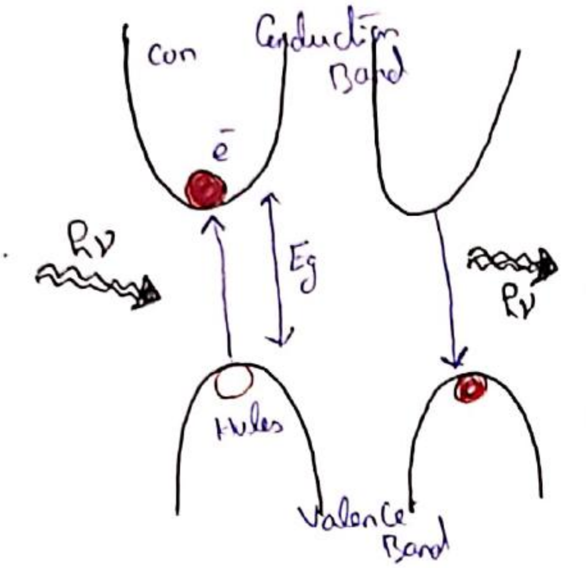
⊛ The external light source such as polariser and analyser are required.

PHOTO PROCESSES :-

⊛ The operation of optoelectronic devices is based on the creation of electron-hole pairs so called 'photo process'

⊛ Photon with sufficient energy are absorbed the electron-hole pair are created i.e. Carrier Generation.

⊛ The reverse process is electron- hole reCombination, give up its energy is Charges ReCombination



Charge Generation & ReCombination

The reCombination may be two type:

i) Non- radiative Process

ii) Radiative Process.

i) Non- radiative Process:

The excess energy due to reCombination is usually imparted to phonon and dissipated in the form of heat.

ii) Radiative Process:

The excess energy is dissipated as photon usually having energy equal to band gap, emits light.

QUANTUM CONFINEMENT :-

It is a process of reducing the size of a cubic solid, so that the energy level inside become descrete.

⊛ It is observed when the size of the particle is too small compare to the wavelength of the electron.

⊛ In which only small percent of electron free to move during confinement.

⊛ By bottom up or Top down process the dimension reduced.

QUANTUM STRUCTURE :-

When a bulk material reduced in its size. If the reduced dimension is in the order of few nanomaterials, then the structure is known as "Quantum structure".

It is classified into 3 types based on direction.

i) Quantum well
ii) Quantum wire.
iii) Quantum Dot.

i) Quantum Well:-

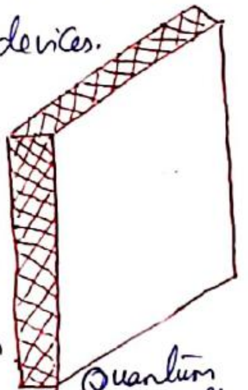
If one dimension is reduced to nano range while the other two dimension remain large, then we get a structure known as "Quantum well".

⊛ Quantum well are made from alternative layer of different semiconductor or by deposition of very thin metal film.

⊛ It is a large structure in which the carrier particle are free to move in 2D.

⊛ The particle are confined in one Dimension, they are considered as Quantum Confinement.

⊛ Confinement of carriers, the quantum well structure has important application to making devices.



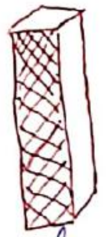
Quantum well.

ii) Quantum Wire:-

⊛ If 2D are reduced and one dimention remain large, the resulting structure, "Quantum Wire".

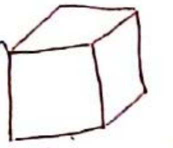
⊛ The carrier are free to move its trajectory along the wire.

⊛ Quantum wire structure are nanowire, nanorod and nanotude.



Quantum Wire

iii) Quantum Dots:-

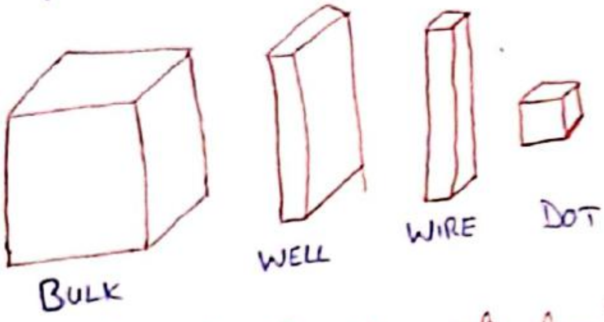


⊛ All three dimension are minimized, the rescelting structure is known as "Quantum Dot".

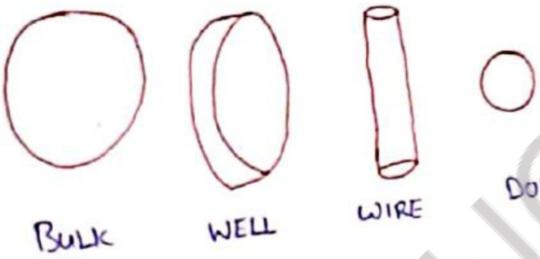
⊛ The Carriers has only Confined state ie not freely moving.

⊛ It has many thousand of atom, Carrier are Considered a single atom due to its peculiar properties.

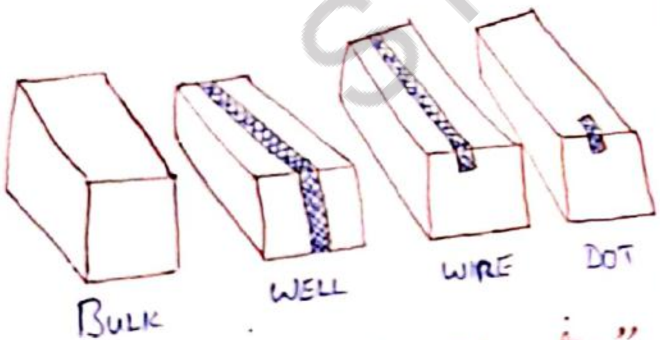
⊛ It is used in a quantum Computer and quantum dot laser etc



"Rectangular Nano structure"



"Curvilinear Nano Structure"



"Three Quantum Structure"

DENSITY OF STATE IN QUANTUM WELL, QUANTUM WIRE & QUANTUM DOT:-

Bulk Structure:

Density of State $Z(E) = \dfrac{8\pi\sqrt{2}\, m^{*3/2}(E-E_c)^{1/2}}{h^3}$

E_c => Bottom of Conduction Band Energy

m^* => Effective Mass of electron.

Quantum Well:

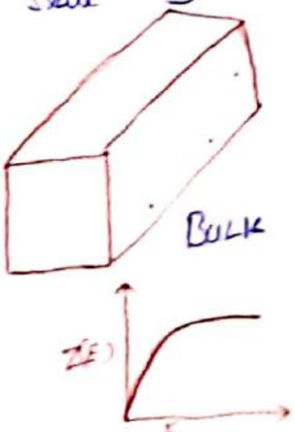
⊛ The electron can move freely in two dimension and Confined in only one direction.

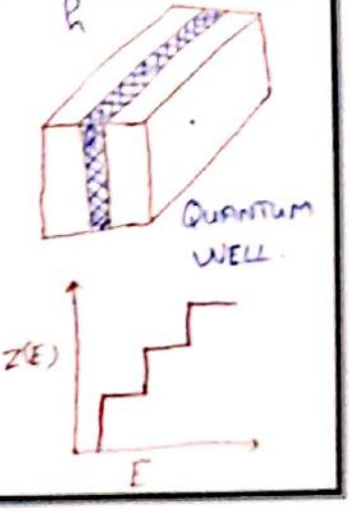
Density of State $Z(E) = \dfrac{4\pi m^*}{h^2}$ $E_0 > E_i$; $i = 1, 2, 3$.

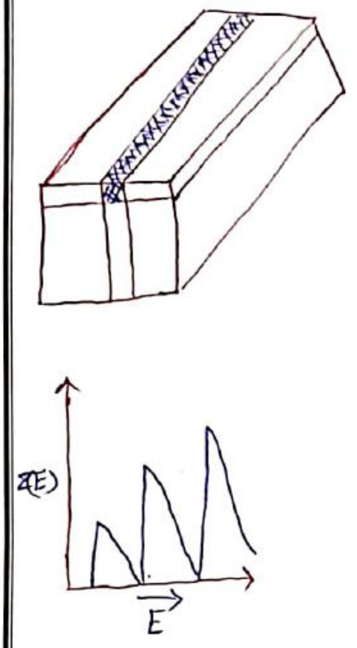
Quantum Wire:

⊛ It provide only one non-Confinement direction, it can move only one direction; the remaining two direction are Confined for charge Carrier.

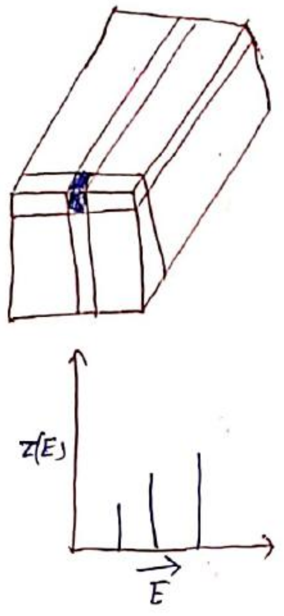
Density of State $Z(E) = \dfrac{2\sqrt{2}\, m^*(E-E_i)^{-1/2}}{h}$; $i = 1, 2, 3$.







QUANTUM WIRE



QUANTUM DOT.

SINGLE ELECTRON TRANSISTOR: (SET)

⊛ SET is three-terminal switching device which can transfer electron from source to drain one by one.

⊛ SET is individually control the tunneling of electron into and out of the quantum dot.

Construction & Working:-

⊛ Apply voltage bias to the gate voltage; Voltage difference occurs between source & Drain. That the current and electron flow in the same direction, from which the electron are orginate.

⊛ Gate voltage creat an electric field that alter the conductivity of the semiconducting channel below it, enabling current to flow from source to Drain

⊛ Due to electric field, change in potential energy in dot w.r.t to Source and Drain

⊛ Gate voltage-controlled potential difference make electron in the source attracted to the dot, simultaneously electron in the dot attracted to the drain.

Energy need to move a charge Q, across the potential difference 'V'.

$$E = VQ.$$

$$V = \frac{E}{Q} = \frac{E}{e} = \frac{W_c}{e}$$

$\because$ Q ⇒ Charge of Electron, 'e'

W_c ⇒ Charging Energy.

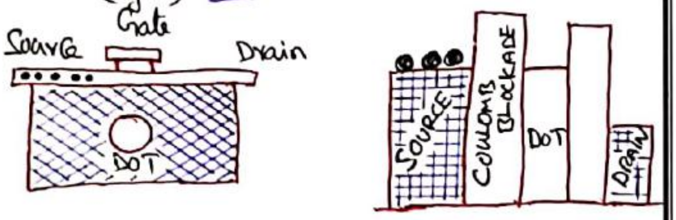
$$V = \frac{e}{2C} \qquad \boxed{\because W_c = e^2/2C}$$

This much of voltage require to electron tunnel through Coulomb blockade of Quantum dot.

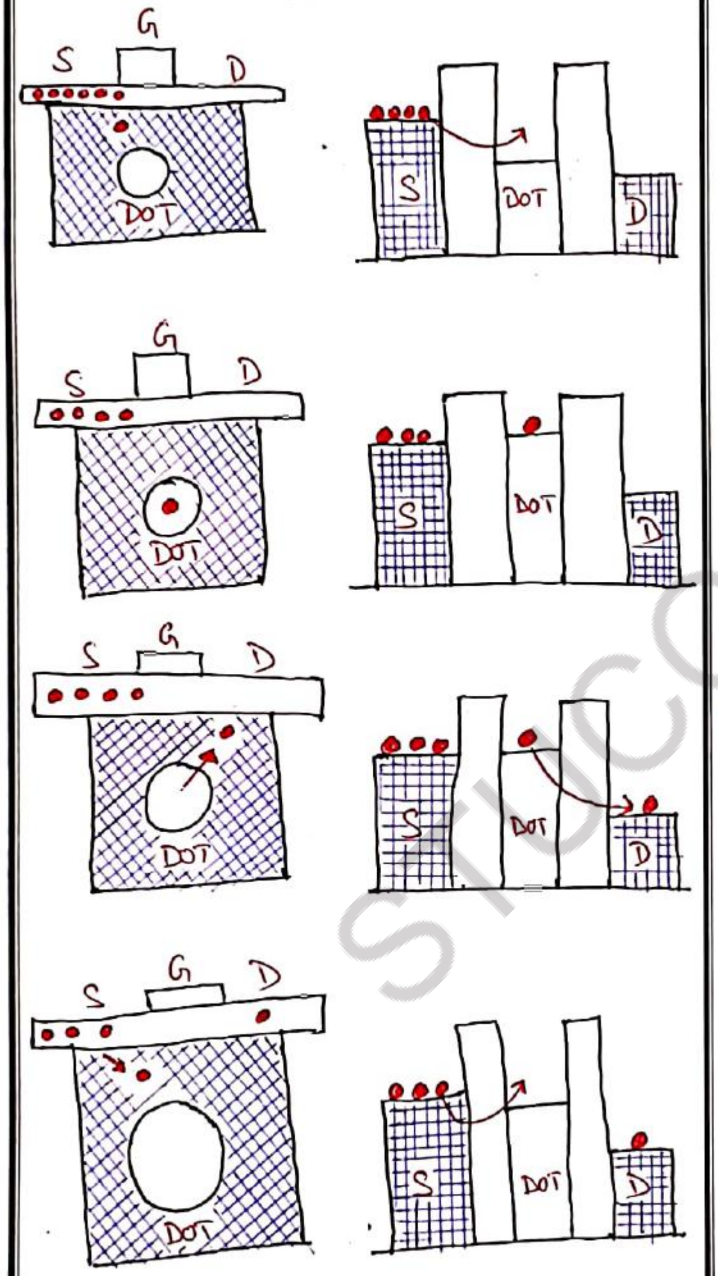
Working:-

The SET has an electrically isolated quantum dot located between the source & drain.

($V_g=0$) OFF MODE



ON MODE



⊛ SET in "OFF" Mode, it is not energitically favorable for electron Source to dot via tunnel.

⊛ SET in "ON" Mode, electron tunnel one at a time via the dot from source to drain.

⊛ Apply proper gate voltage, the potential energy of dot is low to encourage electron to tunnel through energy barrier.

⊛ The electron is on it, the dot potential energy rises as in fig.

⊛ Electron then tunnel through the Coulomb blockade on the other side to reach the lower potential energy at the drain.

⊛ The dot empty and the potential lower again, the process repeats.

Application:-

→ SET is used in sensor technology and digital electronic circuits

→ It is used for mass data storage.

→ It is used in highly sensitive electrometer

→ SET is suitable measurement set-up for single electron spectroscopy.

CARBON NANOTUBE :- [CNT]

The hexagonal lattice of Carbon is simply graphite. A single layer of graphite is called "Graphene".

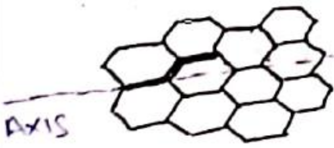
When the graphene layer is rolled, the structure is tube like and it is a single molecule, and is made up of a hexagonal network of Covalently bonded Carbon atom.

Type of CNT :-

Three type of nanotube structure are Considered by rolling a graphite sheet base on axis,

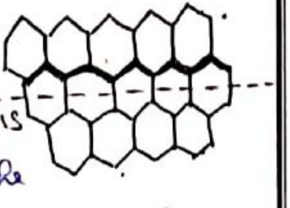
- i) Arm Chair structure
- ii) Zig-Zag structure
- iii) Chiral structure.

i) Arm Chair Structure :-



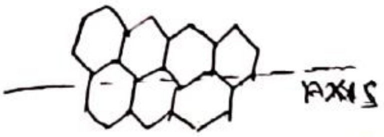
When the axis of tube parallel to C-C bond of the Carbon hexagons.

ii) Zig-Zag Structure :-



This structure are formed by rolling graphene sheet such the axis of the tube is not parallel to C-C bonds, its perpendicular to C-C bonds.

iii) Chiral Structure :-



In chiral structure, C-C bond is inclined towards the axis of the tube.

Properties of CNT :-

i) Electrical Properties :-

- Carbon nanotube are metallic or semiconducting depending on the diameter or chirality.
- Energy gap of semiconducting chiral Carbon nanotube is inversely proportional to the diameter of the tube.
- The energy gap also varies along the tube axis and reaches a minimum value at the tube end.

ii) Mechanical Properties :-

- Structured based on aligned Carbon-Carbon bond will ultimately high strength.
- One of the important properties of nanotube is ability to withstand extreme strain.
- It have high ultimate tensile - strength.

iii) Physical Properties :-

- The surface area of nanotube is the order of 10-20 m^2/g which is higher than graphite.

iv) Chemical Properties:-

It is difficult to osidize them and the onset of osidation in nanotube is 100°C higher than that of Carbon fibres.

As a result, temperature is not a limitation in practical application of nanotubes.

v) Thermal Properties:

It have a high thermal Conductivity and the value increase with decrease in diameter.

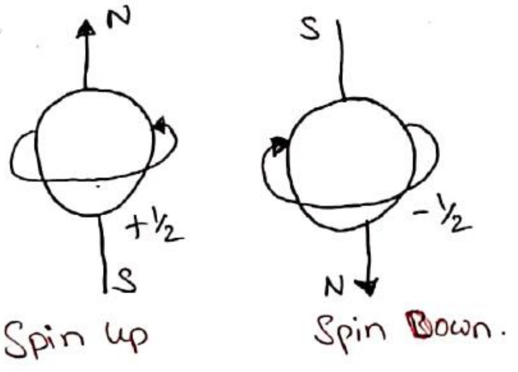
Application:

- It is used in development of flat panel display.
- It is used to make a Computer switching devices.
- It Canbe used for Storing the hydrogen, which is used in the development of fuel Cell.
- It Canbe used to increase the tensile strength of steel
- It act as Catalyst for some chemical reactions

SPINTRONICS:-

Spintronics is a NANO technology which deals with spin dependent properties of an electron instead of charge dependent properties.

- Spintronics is based on the Spin of electron rather than its charge.
- Electron exists one of two state - Spin up and spindown (or) Clockwise and anticlock wise. represent '0' and 1.



Spin up Spin Down.

Explanation:-

Spining of electron likes a tiny magnet with north and south pole The orientation of north-south axis depends on the particle axis of Spin.

For ordinary material, the magnetic moment cancel to each other, but in ferro magnetic material, it exhibits magnetic properties. This result in a permanent magnet.

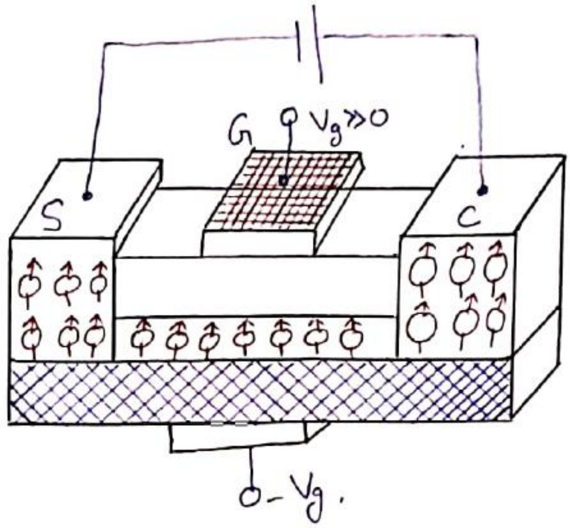
Working :-

All spintronic devices act in simple scheme;

- Information is stored into spin as a particular spin orientation (up or down).
- The spins, being attached to mobile electron, carry information along a wire and the information is read at a terminal.
- Spin orientation of electron in spintronic device useful for memory storage and magnetic sensor application.
- These are used for quantum computing, electron spin will represent a bit (qubit) of information. When electron spins are alligned this create a large scale net magnetic moment.

SPIN-FET :-

A spin based field Effect Transistor ie SPIN-FET.



First the spins have to be injected from source into the non-magnetic layer and then transmitted to the collector.

The injected spin which are transmitted through this layer start precessing as in fig., before they reach the collector due to the spin-orbit coupling effect.

Hence, the net spin polorization is reduced. In order to solve this problem an electrical field is applied ⊥r to the plane of the film by depositing a gate electrode on the top to reduce the spin-orbit coupling effect.

If V_g is zero, net spin polarization are reduced before they reach the Collector.

If $V_g \gg 0$, the precession of electron is Controlled by electric field to reach the Collector with the same polarization.

By Controlling the gate voltage and polarity, the Current in the Collector Can be modulated just like the MOSFET of the Conventional electronics.