ELECTRICAL PROPERTIES OF MATERIALS

Classical Free Electron theory of metals

1. The classical free electron theory was first proposed by Lorentz-Drude in 1900.

2. According to this theory, a metal consist of large number of atoms and these atoms have nucleus at the center and electrons are revolving round the nucleus.

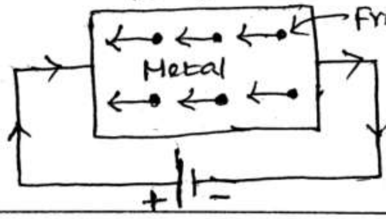
3. The Electrons at the outermost orbit are called "Valence electrons" or free electrons or conduction electrons.

4. These free electrons move to any direction randomly just like molecules of a gas.

5. When an electric field is applied to the metal, these free electrons moves in the direction opposite to the direction of applied electric field.

6. The average velocity acquired by the electrons in the same direction due to the application of electric field is called "Drift Velocity". (ie) $V_d = \mu E$ Where, μ = Mobility of electron, E = Electric field

7. The average drift velocity acquired by the electrons per unit electric field is called "Mobility". (ie) $\mu = \frac{V_d}{E}$

8. 

The time taken by the electrons to reach its equilibrium position from its disturbed position is called "Relaxation Time".

9. The average time taken by the free electrons between two successive collision is called "Collision Time".

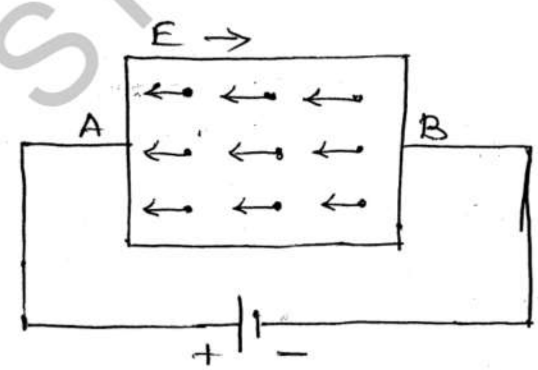
Expression for Electrical conductivity of the conductor

Definition:

"The amount of current flowing through unit area of cross section of the material per unit time at constant potential difference" is called Electrical conductivity.

Expression:

1. Let us consider a conductor with two sides A & B connected to the Battery as shown in the figure.



2. When an electric field 'E' is applied between AB, then the electrons move from end B to end A in the same direction.

3. The electric force acting on free electron $\boxed{F = eE}$ —— (1)

But, According to Newtons Law $\boxed{F = ma}$ —— (2)

Where, e = charge of Electron
E = Electric field
m = Mass of Electron
a = Acceleration

By Comparing (2) = (1)

$$ma = eE$$

$$\boxed{a = \frac{eE}{m}} \quad \text{—— (3)}$$

4. But, We know, Acceleration $a = \frac{\text{Drift Velocity}}{\text{Relaxation Time}} = \frac{V_d}{\tau}$

(ie) $\boxed{a = \frac{V_d}{\tau}}$ —— (4)

By comparing (4) = (3)

$$\frac{V_d}{\tau} = \frac{eE}{m}$$

$$\boxed{V_d = \frac{eE}{m}\tau} \quad \text{—— (5)}$$

5. We know, Drift Current Density $\boxed{J = neV_d}$ —— (6)

sub. eqn (5) in (6)

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

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

6. But, Drift Current Density also $\boxed{J = \sigma E}$ —— (8)

$\therefore$ (8) = (7)

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

(i.e) $$\boxed{\sigma = \frac{ne^2\tau}{m}} \quad \text{--- (9)}$$

This is the equation for Electrical conductivity of a conductor.

Expression for Thermal conductivity of the conductor

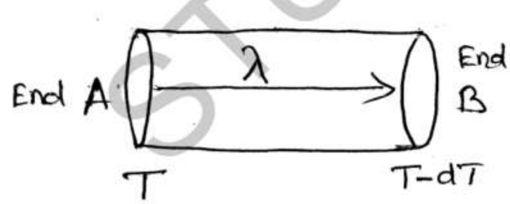
Definition:

"The amount of heat flowing through unit area of cross section of the material per unit time at constant Temperature difference" is called Thermal conductivity.

Expression

1. Let us consider a conductor in the form of rod with 2 ends A & B seperated by a distance 'λ'.

2.



Let,
T = Temperature at end A
$T-dT$ = Temperature at end B
λ = Mean free path or distance for electrons

3. The average K.E of electrons at end A $= \frac{3}{2}kT$ --- (1)

The average K.E of electrons at end B $= \frac{3}{2}k(T-dT)$ --- (2)

where, k = Boltzmann's constant
T = Temperature

4. The excess of energy in electrons ① − ②

$$= \frac{3}{2}kT - \frac{3}{2}k(T-dT)$$

$$= \frac{3}{2}kT - \frac{3}{2}kT + \frac{3}{2}kdT$$

$$= \frac{3}{2}kdT$$

5. But, the number of electrons crossing the shortest distance from A to B $= \frac{1}{6}nv$

6. So, the excess of energy carried by the electrons from A to B $= \frac{1}{6}nv \times \frac{3}{2}kdT$

$$= \frac{1}{4}nvkdT \quad \text{--- (3)}$$

The deficiency of energy carried by the electrons from B to A $= -\frac{1}{4}nvkdT$ — ④

7. Hence, Net Heat Energy transferred is eqn ③ − ④

$$Q = \frac{1}{4}nvkdT - \left(-\frac{1}{4}nvkdT\right)$$

$$\boxed{Q = \frac{1}{2}nvkdT} \quad \text{--- (5)}$$

8. As per definition

Heat flows in a conductor $Q = K\frac{dT}{dx}$

Where, $\{dx = \lambda\}$

(or) $\boxed{Q = K\frac{dT}{\lambda}}$ — ⑥

K = Thermal conductivity

9. Comparing eqn (5) & (6)

(6) = (5)

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

$$\boxed{K = \frac{1}{2} n v k \lambda} \quad \text{——— (7)}$$

This is the equation for Thermal conductivity of conductor.

Wiedmann – Franz Law

Wiedmann – Franz law states that the ratio between thermal conductivity and electrical conductivity of the conductor is directly proportional to absolute temperature.

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

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

Where,

L = Lorentz number

Proof :-

$$\frac{K}{\sigma} = \frac{\frac{1}{2} n v k \lambda}{n e^2 \tau / m}$$

But we know

$$\text{Velocity}(v) = \frac{\text{Distance}(\lambda)}{\text{Time}(\tau)} \; ; \; v = \frac{\lambda}{\tau} \; (\text{ie}) \; \tau = \frac{\lambda}{v}$$

$$\therefore \frac{K}{\sigma} = \frac{\frac{1}{2} n v k \lambda}{n e^2 \lambda / v m} = \frac{1}{2} \frac{m v^2 k}{e^2}$$

But from K.E equation

$$\frac{1}{2}mv^2 = \frac{3}{2}kT$$

$$\therefore \frac{K}{\sigma} = \frac{\frac{3}{2}kT \times k}{e^2}$$

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

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

Where, $L = \frac{3}{2}\left(\frac{k^2}{e^2}\right)$ → Lorentz Number.

Hence, Wiedmann-Franz Law proved

Success of Classical free electron theory

1. It verifies ohms law
2. It explains electrical and thermal conductivities of metals.
3. It is used to derive Wiedmann-Franz law.
4. It is used to explain the optical properties of metals.

Failure or Drawbacks of Classical free electron theory

1. It cannot explain photoelectric effect and Black body radiation
2. It cannot explain electrical conductivity of Semiconductor or Insulator.
3. $K/\sigma T$ is not constant at low temperatures for metals.
4. The theoretical value of specific Heat of metals do not matches with experimental Value.
5. It cannot explain ferromagnetism

Quantum Free Electron theory

1. The drawbacks of classical free electron theory can be rectified using quantum theory.
2. In 1928, Sommerfeld used Fermi-Dirac statistics to solve the problems in classical theory.
3. The following assumption are made in quantum theory
   (i) The electrons shows wave nature
   (ii) The electrons are distributed in solid by FD statistics.
   (iii) The potential of electron is constant in a crystal solid.
   (iv) The permitted energy levels of an electron are quantized.
   (V) The physical properties of solid depend on the number of free electrons available at the Fermi energy level.

Merits of Quantum Free Electron theory

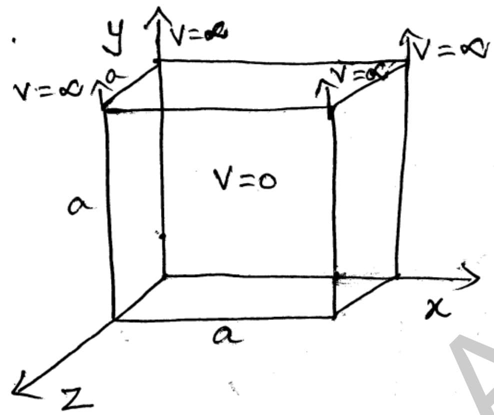
1. It explains correct value of electrical, thermal conductivities and specific heat capacity of metals.
2. It explains photoelectric effect and compton effect.
3. It also explains semiconductor and insulators.

Demerits of Quantum Free Electron theory

1. It cannot differentiate metals, semiconductors, Insulators.
2. It fails to explain charge transport properties in metals.

Particle in a 3D Box

1. consider a 3D metal Box in which electrons move in all direction.



2. Let, n_x, n_y, n_z = quantum numbers for moving electrons along x, y, z axes.

3. The Boundary condition for electrons in a 3D box are

$x=0, y=0, z=0$; $V=\infty$ and $x=a, y=a, z=a$; $V=\infty$

and $0<x<a$, $0<y<a$, $0<z<a$; $V=0$

4. The Schrodinger wave equation becomes

$$\frac{d^2\psi}{dx^2} + \frac{d^2\psi}{dy^2} + \frac{d^2\psi}{dz^2} + \frac{2m}{\hbar^2} E\psi = 0$$

5. Solution for the above equation is

$$\psi_{(x,y,z)} = A_x \sin k_x x \; A_y \sin k_y y \; A_z \sin k_z z$$

Where, $k_x = \frac{n_x \pi x}{a}$, $k_y = \frac{n_y \pi y}{a}$, $k_z = \frac{n_z \pi z}{a}$

6. By applying boundary condition, we get

$$A_x = \sqrt{\frac{2}{a}}, \quad A_y = \sqrt{\frac{2}{a}}, \quad A_z = \sqrt{\frac{2}{a}}$$

7. The wave function for electrons in 3D Box

$$\psi_{n_x n_y n_z} = \sqrt{\frac{2}{a}} \sin\frac{n\pi x}{a} \sqrt{\frac{2}{a}} \sin\frac{n\pi y}{a} \sqrt{\frac{2}{a}} \sin\frac{n\pi z}{a}$$

8. The Energy of electrons in 3D Box

$$E_{n_x n_y n_z} = \frac{(n_x^2 + n_y^2 + n_z^2) \times h^2}{8ma^2}$$

Degenerate State

For different combination of quantum numbers if we have same energy values and different wave functions, then it is called "Degenerate State". (Ex) (112), (121), (211).

Non Degenerate State

For different combination of quantum numbers if we have same energy values and same wave functions, then it is called "Non-Degenerate State". (Ex) (111), (222), (333).

Fermi-Dirac Statistics

1. The spin of the electrons in an atom is explained by the statistical concept which is called "Fermi-Dirac statistics".

2. Using this statistics, we can find the electron occupation in an energy level using the function called "Fermi Function".

3. The probability value of finding the occupation of electrons at any temperature is called "Fermi Function" (F(E)). It is given by

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

E = Total Energy
E_F = Fermi energy
k = Boltzmanns constant
T = Temperature

4. The effect of temperature on fermi function is given below

case (i)

If $T = 0\,k$, $E > E_F$

Then,
$$F(E) = \frac{1}{1+e^{E-E_F/0}} = \frac{1}{1+e^{(+ve)/0}}$$
$$= \frac{1}{1+e^{\infty}}$$
$$= \frac{1}{1+\infty} = \frac{1}{\infty}$$
$$F(E) = 0$$

Case (ii)

If $T = 0K$, $E < E$

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

$= \frac{1}{1+0}$

$F(E) = 1$

Case (iii)

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

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

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

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

5. Each energy levels can have only one electron with 1 spin.
6. If there is 'n' number of electrons, there will be 'n' number of energy levels available for occupation.
7. The electrons which obeys the F-D Statistics are called fermions.
8. The total energy of the system = Sum of all energies of the electrons.

Density of Energy States

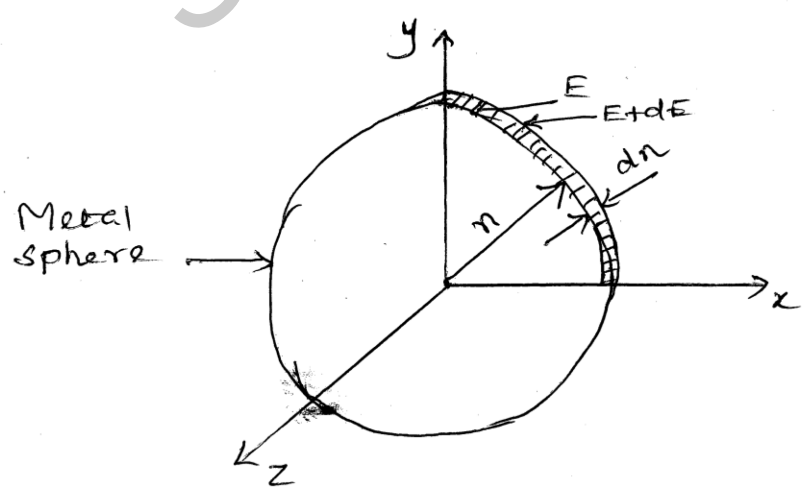
Definition

The density of states in a metal is defined as "the number of states per unit volume in an energy interval E and E+dE."

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

Derivation

1. Let us consider a metal in a spherical shape in 3D space.
2. Let dn = Thickness of sphere on the surface
   n = Inner radius of sphere
   n+dn = Outer radius of sphere
   E = Energy value at radius 'n'.
   E+dE = Energy value at radius 'n+dn'.
3. consider $\frac{1}{8}^{th}$ volume of sphere



4. The number of states between n and $n+dn$ is $N(E)dE$

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

$$= \frac{\pi}{6} \times 3n^2 dn$$

$$N(E)\,dE = \frac{\pi}{2} n^2 dn \quad \text{--- (1)}$$

5. We know,

The Energy Value of electron $E = \dfrac{n^2h^2}{8ma^2}$ --- (2)

Differentiating above equation $dE = \dfrac{2n\,dn\,h^2}{8ma^2}$ --- (3)

6. From eqn (3) we can write $n\,dn = \dfrac{8ma^2 dE}{2h^2}$ --- (4)

∴ Eqn (2) becomes $n = \left(\dfrac{8ma^2E}{h^2}\right)^{1/2}$ --- (5)

7. Rewriting eqn (1) as,

$$N(E)dE = \frac{\pi}{2}\, n \times n\,dn \quad \text{--- (6)}$$

Sub eqn (4) & (5) in eqn (6)

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

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

$$= \frac{\pi}{4h^3}\, 8 \times 8^{1/2}\, m^{3/2} \times 1 \times E^{1/2} dE$$

$$= \frac{\pi}{4h^3}\, 8 \times 2^{3/2}\, m^{3/2}\, E^{1/2}\, dE \qquad \{a^3 = 1 \text{ unit Volume}\}$$

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

9. If 2 Electrons occupy every state, then

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

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

10. Hence, the Density of States

$$Z(E)\,dE = \frac{N(E)\,dE}{V} \qquad V = a^3 = 1$$

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

Note

(i) Calculation of Carrier concentration (or) Number of electrons in a metal, (n)

At the temperature 0K, F(E) = 1

$$n = \int_0^{E_F} Z(E)\,dE \times F(E)$$

$$\therefore n = \int_0^{E_F} \frac{4\pi}{h^3}(2m)^{3/2} E^{1/2}\,dE \times 1$$

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

$$\boxed{n = \frac{8\pi}{3h^3}(2m)^{3/2} E_F^{3/2}}$$

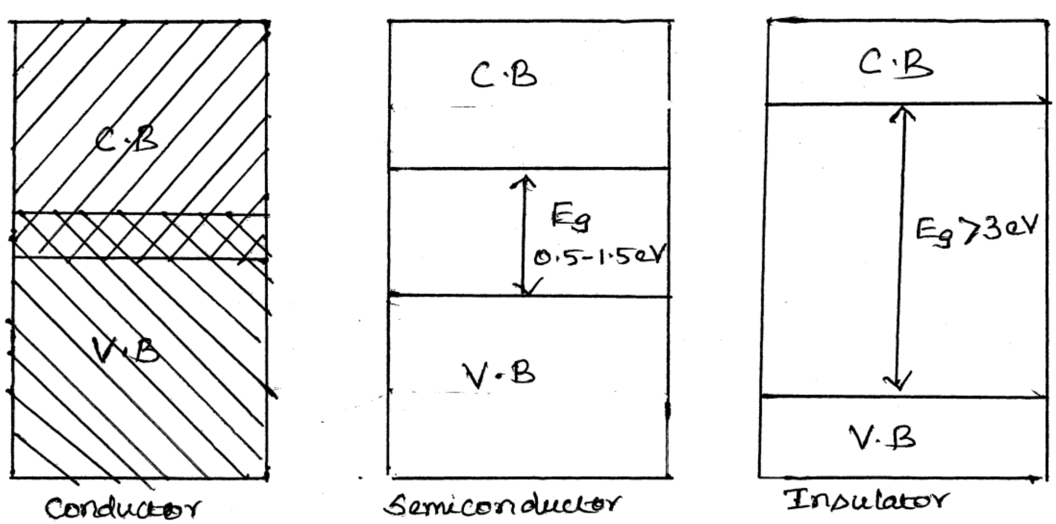
(ii) Calculation of Fermi Energy (E_F)

$$E_F^{3/2} = \frac{3h^3}{8\pi} \cdot \frac{n}{(2m)^{3/2}}$$

$$\boxed{E_F = \left(\frac{h^2}{2m}\right)\left(\frac{3n}{8\pi}\right)^{2/3}}$$

Energy Bands in Solids

1. A solid consist of large number of atoms closely packed together.
2. The electrons at the outermost orbit in an atom has weak interaction with nucleus. So, they can easily detatched from the atom. Thes electrons are called "Free Electrons".
3. The intermixing of Valence orbits of atom forms energy bands called "Valence Band".
4. The intermixing of Empty orbits of atom forms energy bands called "Conduction Band".
5. The space between V.B and C.B is called "Band Gap" or "Forbidden Gap".
6. If the temperature of the material is increased, the free electrons moves from V.B to C.B.
7. The materials can be classified based on the width of the energy gap as (i) conductor (ii) Semiconductor (iii) Insulator.



8. If there is no energy gap between V.B and C.B, then the material is called 'conductor'.

9. If the energy gap between V.B and C.B is about 0.5–1.5 eV, then the material is called "Semiconductor".

10. If the energy gap between V.B and C.B is above 3 eV, then the material is called "Insulator".

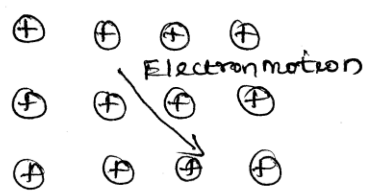
Electron in a periodic potential

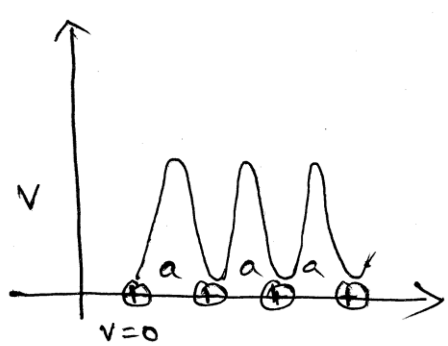
1. The quantum theory fails to explain why some solids are conductors, some are semiconductor and some are insulators.

2. A solution to this problem was given by Band theory (or) Zone theory.

3. According to this theory, electrons move freely inside the crystal and its potential energy changes periodically.

4. If an electron approaches +ve nucleus, the potential is zero and is maximum in between the nucleus.





5. The Schrodinger wave equation in 1D is given by

$$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2} E\psi = 0 \quad \text{--- (1)} \quad \{ \text{If } V = 0 \}.$$

(or) $$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2}(E - V_0)\psi = 0 \quad \text{--- (2)} \quad \{ \text{If } V = V_0 \}.$$

6. The solution for the equations is $\psi = e^{\pm ikx} U_k(x)$ --- (3)

Where, $U_k(x) = U_k(x+a)$

7. Equation (3) is called "Bloch Function" which represents, the electrons moves freely through the potential field of + ion nucleus of an atom.

Tight Binding Approximation

1. The band structure in solids were explained by 2 models such as (i) Free Electron approximation
(ii) Tight binding approximation

2. In free electron approximation, Solid consist of large number of atoms in which electrons are tightly bound with nucleus. But only valence electrons are free to move through the solids.

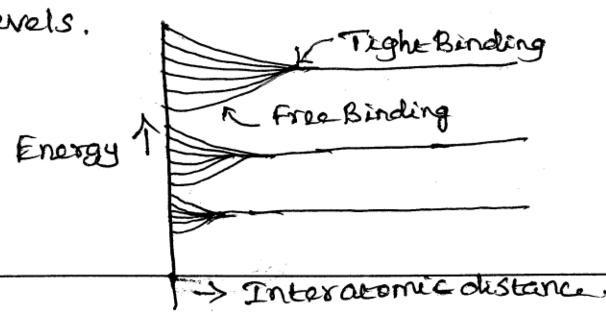
3. But in tight binding approximation, the atoms are free to move and the electrons are tightly bounded.

4. If the atoms are seperated to a large distance, the bound electron in each atom have fixed energy levels.

5. If the atoms are brought close together to form solid, the electrons at the outer orbit are forced to split the energy levels, But inner orbits electrons still maintain their energy levels.

6. If interatomic distance distance decreases further, more and more inner orbit electron energy levels will overlap and splits the energy levels.

7. For example, If 100 atoms come close together which has only one electron at the outer orbit, the solid split the energy levels to 100 energy levels.



Effective mass of Electron and Concept of Hole

1. Definition

The mass acquired by the electron when it is accelerated in a periodic potential is called "Effective mass of Electron".

2. When the electron is accelerated by an electric or magnetic field in a periodic potential, the mass of the electron changes. The varying mass is called "Effective Mass".

3. Let us consider a crystal material subjected to electric field (E). The electrons in the material gains the velocity which is called "Wave Vector" (K).

4. According to wave mechanics, a particle moving with a velocity is equal to a wave packets moving with a group velocity (V_g).

∴ Group Velocity of electron $\boxed{V_g = \frac{d\omega}{dk}}$ —— ①

Where, ω = Angular velocity
k = Wave Vector

5. We know,

$$\omega = 2\pi\nu$$

$$\omega = 2\pi \frac{E}{h} \quad \text{—— ②} \qquad \left\{ \because E = h\nu,\ \nu = \frac{E}{h} \right\}$$

So, eqn ① becomes

$$V_g = \frac{d}{dk}\left(2\pi \frac{E}{h}\right)$$

$$= \frac{2\pi}{h} \cdot \frac{dE}{dk}$$

$$V_g = \frac{1}{\hbar} \frac{dE}{dk} \quad \text{—— ③} \qquad \left\{ \hbar = \frac{h}{2\pi} \right\}.$$

6. The acceleration of Electron $a = \frac{dv_g}{dt}$

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

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

7. The momentum of electron $p = \frac{h}{\lambda}$ (From De-Broglie equation)

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

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

$$p = \hbar k$$

Differentiating w.r.t 't' is $\frac{dp}{dt} = \hbar \frac{dk}{dt}$

$$F = \hbar \frac{dk}{dt}$$

$\because \left\{ F = \frac{dp}{dt} \right\}$ By Newtons II Law

$$m^* a = \hbar \frac{dk}{dt} \quad \text{---} (5)$$

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

Sub eqn (4) in (5)

$$\therefore m^* \frac{1}{\hbar}\frac{d^2E}{dk^2} \times \frac{dk}{dt} = \hbar \frac{dk}{dt}$$

Effective mass of Electron $\}$ $m^* = \frac{\hbar^2}{\left(\frac{d^2E}{dt^2}\right)}$

8. If $\frac{d^2E}{dt^2}$ is $+^{ve}$, m^* also $+^{ve}$

If $\frac{d^2E}{dt^2}$ is $-^{ve}$, m^* also $-^{ve}$

If $\frac{d^2E}{dt^2}$ is large, then the electron behaves as light particle

If $\frac{d^2E}{dt^2}$ is Small, then the electron behaves as heavy particle

Concept of Hole

1. The electrons with a $-^{ve}$ effective mass value same as $+^{ve}$ mass, but with $+^{ve}$ charge is called "Hole".

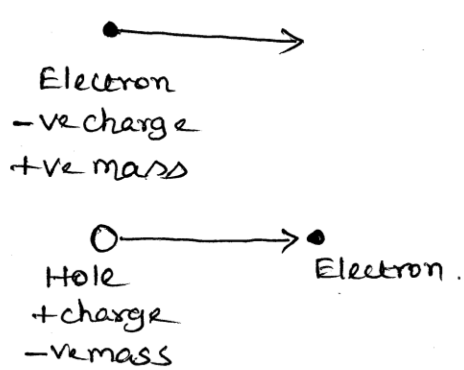
2. The holes are not real particles like electron or neutron.

3. If there is a movement of $-$vely charged electrons, then there is a movement of $+$vely charged holes in the opposite direction.

4. When an electron is displaced, it left an empty space which is called "Hole" with a $+^{ve}$ charge.

5. Normally electrons are filled in valence band of the material Whereas, the holes are filled in conduction band of the material.

6. Based on this hole concept, many phenomenon like Thomson effect, Hall Effect... etc are easily explained.



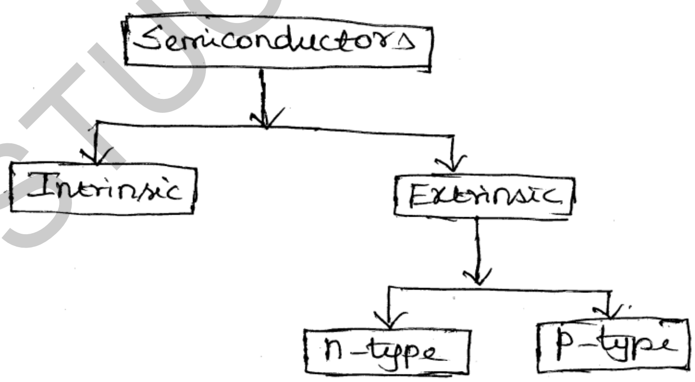
SEMICONDUCTORS

The materials which partially conducts and partially insulates are Called "Semiconductors".

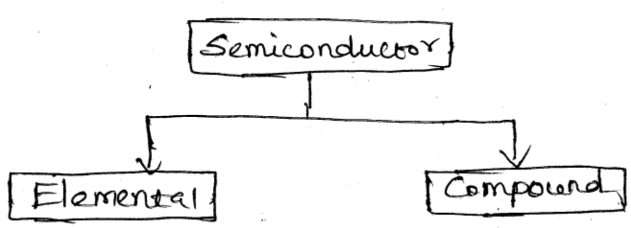
properties

1. The resistivity Value ranges between 10^{-4} and 0.5 ohm-m.
2. The Energy gap Value ranges between 0.5 eV and 1.5 eV.
3. They acts as a conductor at high temperature and acts as a insulator at low temperature.
4. They have -ve temperature coefficient of resistance value.
5. They conducts current due to both electrons and holes.

Types of Semiconductor



General classification



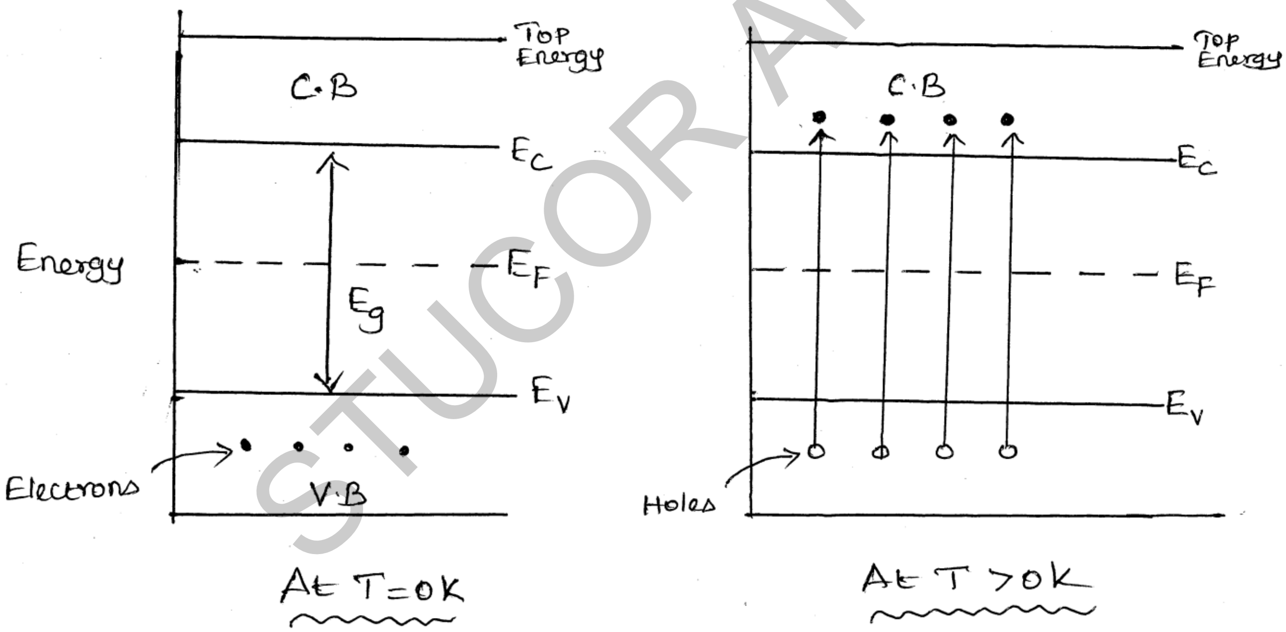
Elemental Semiconductor	Compound Semiconductor
1. It is made up of Single Element from IV column. Eg: Ge, Si	It is made up of two or more elements like III & V or II & VI column. Eg: GaAs, CdSe
2. It is also called Indirect Band Gap Semiconductor.	It is also called Direct Band Gap Semiconductor.
3. Heat is produced during Recombination of Charge Carriers	Light photons are produced during recombination of charge carriers.
4. Life time is more	Life time is less
5. Current amplification is more	Current amplification is less.
6. They are used to make Diodes and transistors	They are used to make LED'S, Laser Diodes and LIC'S

Intrinsic Semiconductor

1. A pure form of Semiconductor is called "Intrinsic Semiconductor".
   Eg : Ge, Si

2. The intrinsic Semiconductors have 4 Valence electrons and these electrons forms covalent bond with neighbourhood atoms.

3. If heat energy is given, the bonds are broken and electrons begins to move from V.B to C.B as shown in the diagram.



4. Let E_V = Valence Energy level
   E_F = Fermi Energy level
   E_C = conduction Energy level

5. The number of electrons in C.B at T > 0K is

$$n = \int_{E_C}^{\text{Top energy}} Z(E)\,dE \times F(E)$$

When,

$Z(E)\,dE$ = Density of states

$F(E)$ = Fermi function

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

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

But,

$e^{E-E_F/kT} >> 1$, so '1' can be neglected in the formula

$$\therefore \quad n = \int_{E_c}^{\infty} \frac{4\pi}{h^3}(2m_e^*)^{3/2}(E-E_c)^{1/2} \times \frac{1}{e^{E-E_F/kT}}$$

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

6. To solve the integration part,

Let $E - E_c = x$

$\therefore \quad E = x + E_c$

$\therefore \quad dE = dx$

Limit change.

if $E = E_c$, then $x = 0$

$E = \infty$, then $x = \infty$

7. Substitute all values in eqn (2)

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

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

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

8. The Sol^n for $\int_0^\infty x^{1/2} e^{-x/kT} dx = \frac{(kT)^{3/2} \pi^{1/2}}{2}$

$$\therefore n = \frac{4\pi}{h^3}(2m_e^*)^{3/2} e^{E_F - E_c/kT} \times \frac{(kT)^{3/2}\pi^{1/2}}{2}$$

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

This equation is for Density of electrons (or) concentration (or) Total number of electrons in C.B in intrinsic semiconductor.

9. IIIrly the Density of holes (or) concentration (or) Total number of holes in V.B in intrinsic semiconductor can be written as

$$p = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} e^{E_v - E_F/kT}$$

10. Intrinsic carrier concentration (n_i)

To calculate total number of both electrons and holes in intrinsic semiconductor, let $n_i = n = p$

$$n_i^2 = np$$

$$\therefore n_i^2 = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} e^{E_F - E_c/kT} \times 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} e^{E_v - E_F/kT}$$

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

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

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

where $E_C - E_V = E_g$

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

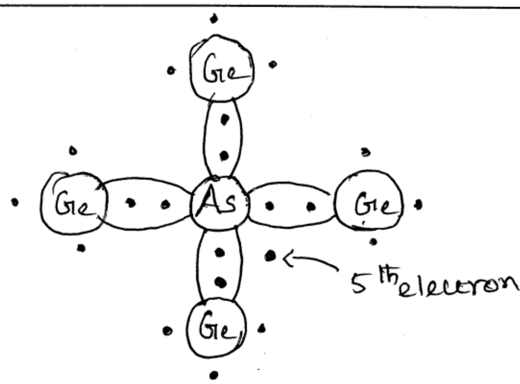
N-Type Concentration

1. Definition:
   When pentavalent impurity atom is added to intrinsic semiconductor, then it is called "n-type semiconductor".

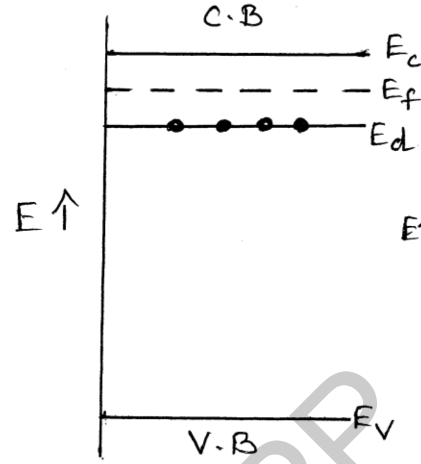
2. The pentavalent materials like As, Sb, P have 5 valence electrons. If these materials are doped with Ge atoms, they form covalent bonds with 4 valence electrons as shown in the diagram.

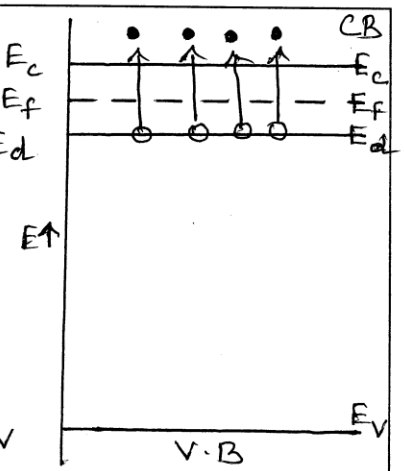
3. The 5th electrons from As is free and donate this electron to Ge. So, all the 5th electrons from As forms "Donor Energy levels" at the bottom of conduction band.

4. The band diagram and structure of n-type semiconductor is shown below,



Structure and Bonding





5. At the temperature T=0K,
The electron concentration (or) density (or) Total number of electrons in C.B is

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

Let

$$N_c = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} \quad \text{——— (A)}$$

$$\therefore \quad n = N_c e^{E_F - E_c/kT} \quad \text{——— (1)}$$

6. III^{ly}, At Temperature T > 0k

The concentration of ionized donor atoms is

$$n = N_d e^{E_d - E_F/kT} \quad \text{——— (2)}$$

7. At equilibrium condition

Number of electrons in C.B = Number of ionized donor atoms

$$N_c e^{E_F - E_c/kT} = N_d e^{E_d - E_F/kT}$$

$$e^{E_F - E_c - E_d + E_F/kT} = \frac{N_d}{N_c}$$

$$e^{2E_F - (E_c + E_d)/kT} = \frac{N_d}{N_c}$$

Taking log on both sides,

$$\frac{2E_F - (E_c + E_d)}{kT} = \log\left(\frac{N_d}{N_c}\right)$$

$$2E_F - (E_c + E_d) = kT \log\left(\frac{N_d}{N_c}\right)$$

$$2E_F = (E_c + E_d) + kT \log\left(\frac{N_d}{N_c}\right)$$

$$\boxed{E_F = \frac{E_c + E_d}{2} + \frac{kT}{2} \log\left(\frac{N_d}{N_c}\right)} \quad (3)$$

If $T = 0k$

then, $E_F = \frac{E_c + E_d}{2}$

If $T > 0k$, sub eqn (3) in eqn (1)

then, $n = N_c e^{\left[\frac{E_c + E_d}{2} + \frac{kT}{2} \log\left(\frac{N_d}{N_c}\right)\right] - E_c / kT}$

$$n = N_c e^{\left[\frac{E_c + E_d}{2} - E_c + \frac{kT}{2} \log\left(\frac{N_d}{N_c}\right)\right] / kT}$$

$$n = N_c e^{\frac{E_c + E_d - 2E_c}{2kT} + \frac{1}{2} \log\left(\frac{N_d}{N_c}\right)}$$

$$n = N_c e^{E_d - E_c/2kT + \log\left(\frac{N_d}{N_c}\right)^{1/2}}$$

$$= N_c \cdot e^{E_d - E_c/2kT} \times \left(\frac{N_d}{N_c}\right)^{1/2} \qquad \left[\because e^{a+b} = e^a \times e^b\right]$$

$$n = (N_c N_d)^{1/2} e^{E_d - E_c/2kT} \quad \text{—— (4)}$$

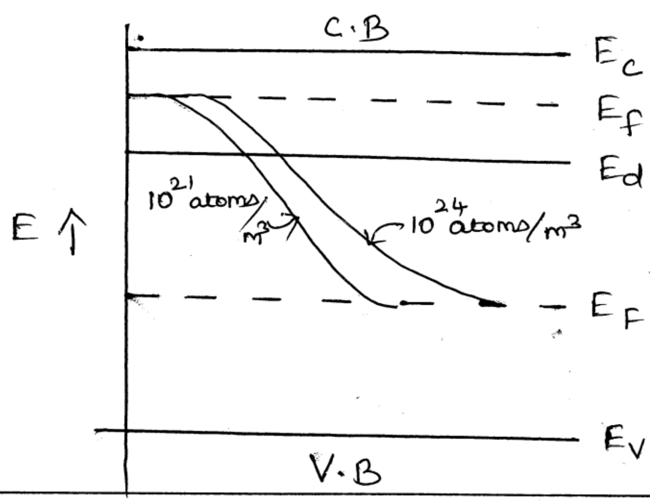
8. Sub eqn (A) in eqn (4)

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

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

This is the equation for concentration of electrons in n-type semiconductor.

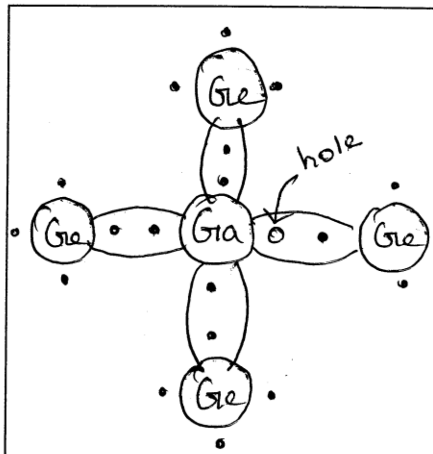
9. Variation of fermi level temperature and donor impurity concentration in n-type semiconductor.



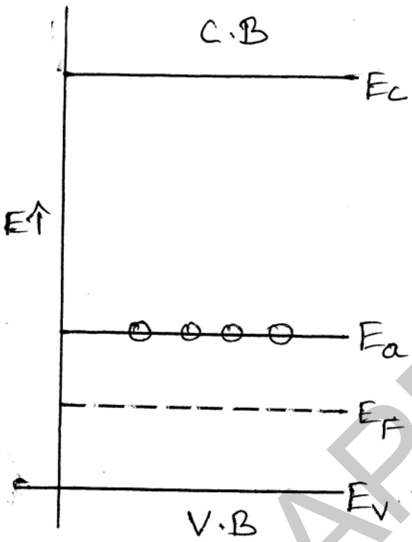
- At T = 0 K, the fermi level is exactly at the middle of E_d & E_c.
- As the temperature increases, more and more donor atoms gets ionized. So, the number of electrons in C.B increases.
- At high temperature, more electron-hole pairs are generated and hence the material becomes intrinsic.
- At high temperature, the fermi level gradually moves downwards to the middle of E_V and E_C.
- The diagram shows that, the lowering of fermi level from E_F to E_F is slow in case of higher donor concentration than lower donor concentration with the increase of temperature.

P-Type Semiconductor

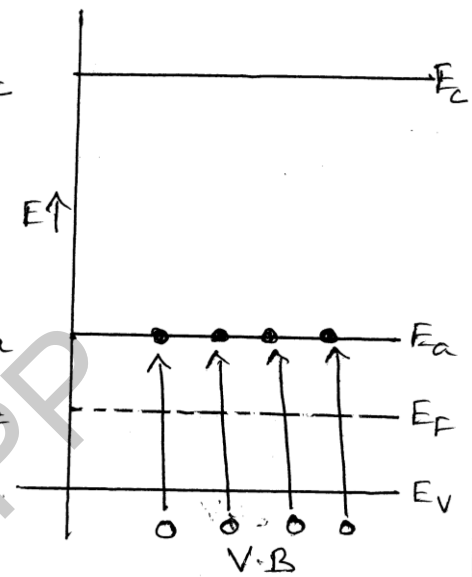
1. Definition:
   When trivalent impurity atoms are added to intrinsic semiconductor, then it is called "P-type Semiconductor".
2. The trivalent materials like Ga, B have 3 valence electrons. If these trivalent materials doped with Ge atoms, they form covalent bond with 3 valence electrons.
3. But the Ga atom accepts the 4^{th} electron from Ge atom to form electron-hole pair.
4. So, all the holes of Ga forms "Acceptor Energy Levels (E_a)" at the top of valence band as shown in the diagram.



Structure and Bonding



At T=0K



At T>0K

5. At the temperature T = 0K

The hole concentration (or) density (or). Total number of holes in V.B is

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

Let,

$$N_V = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} \quad \text{—— (A)}$$

$\therefore$

$$p = N_V e^{E_V - E_F/kT} \quad \text{—— (1)}$$

$|||^{ly}$, At T > 0K, the concentration of ionized acceptor atoms are

$$p = N_a e^{E_F - E_a/kT} \quad \text{—— (2)}$$

6. At the equilibrium condition,

Number of holes in V.B = Number of ionized acceptor atoms

$$N_V e^{E_V - E_F/kT} = N_a e^{E_F - E_a/kT}$$

$$e^{E_V - E_F - E_F + E_a/kT} = \frac{N_a}{N_V}$$

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

Taking log on both sides,

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

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

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

$$\boxed{E_F = \left(\frac{E_V+E_a}{2}\right) - \frac{kT}{2} \log\left(\frac{N_a}{N_V}\right)} \quad (3)$$

7) If T > 0 K, Sub eqn (3) in (1) for E_F

$$P = N_a e^{\left[\frac{E_V+E_a}{2} - \frac{kT}{2}\log\left(\frac{N_a}{N_V}\right) - E_a\right]/kT}$$

$$= N_a e^{\left[\frac{E_V+E_a}{2} - E_a - \frac{kT}{2}\log\left(\frac{N_a}{N_V}\right)\right]/kT}$$

$$= N_a e^{\frac{E_V+E_a-2E_a}{2kT} - \frac{1}{2}\log\left(\frac{N_a}{N_V}\right)}$$

$$= N_a e^{E_V - E_a/2kT - \log\left(\frac{N_a}{N_V}\right)^{1/2}}$$

$$P = N_a e^{E_v - E_a/2kT + \log\left(\frac{N_v}{N_a}\right)^{1/2}}$$

$$= N_a e^{E_v - E_a/2kT} \times \left(\frac{N_v}{N_a}\right)^{1/2} \qquad \left[e^{a+b} = e^a \times e^b\right]$$

$$P = (N_a N_v)^{1/2} e^{E_v - E_a/2kT} \quad \text{——} \quad (4)$$

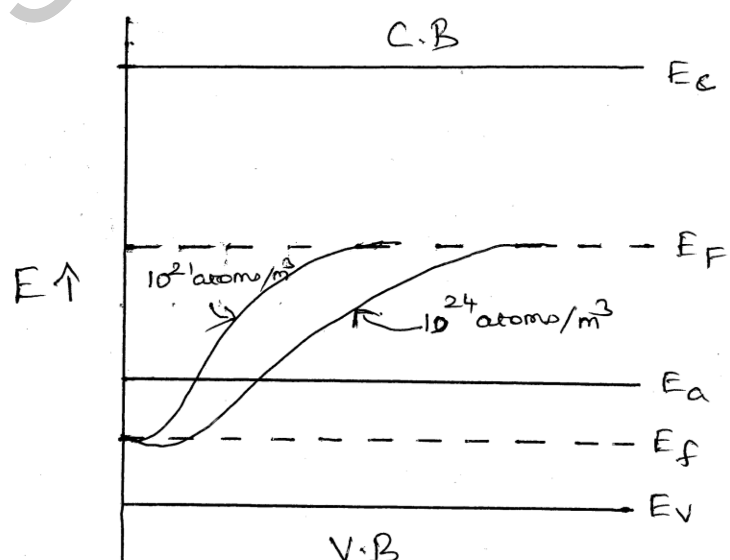
8) Sub the value of N_v [eqn (A)] in the above equation (4)

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

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

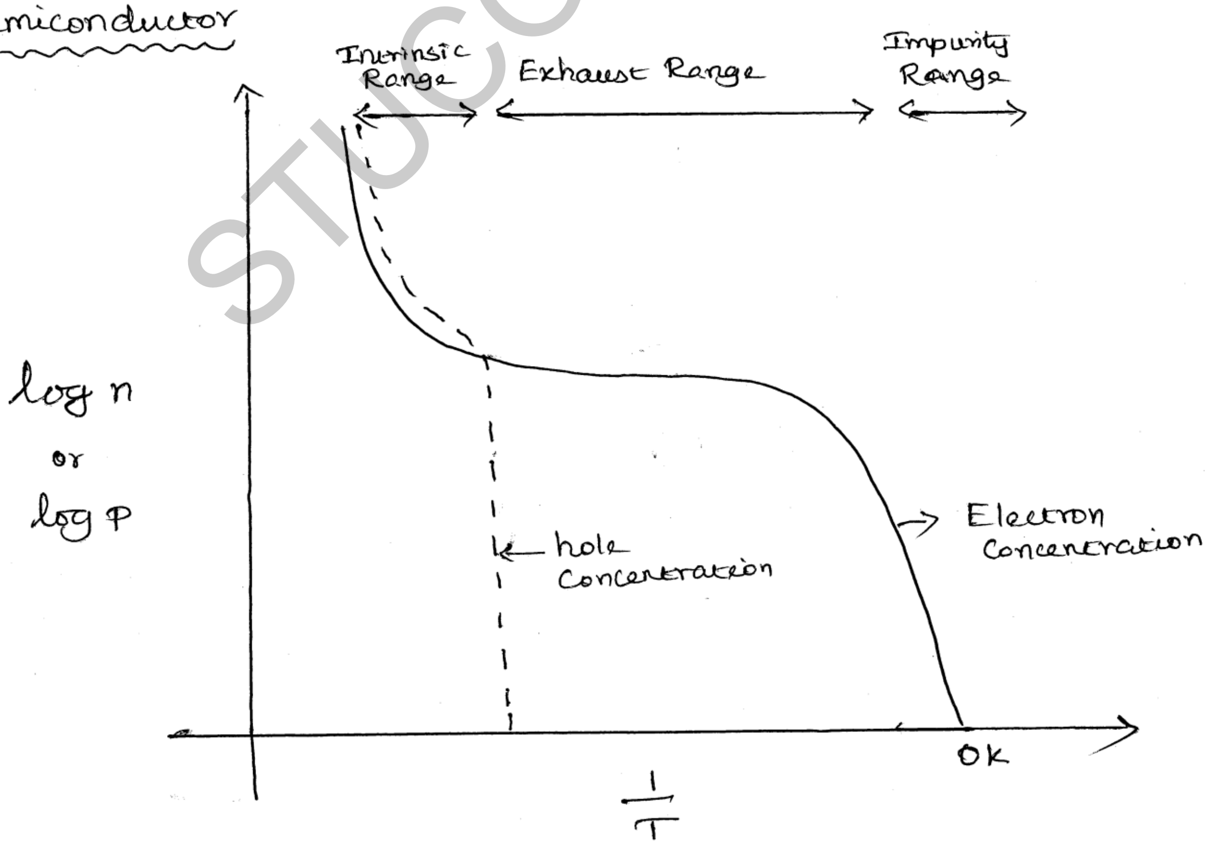
∴ This is the equation for concentration of holes in V.B in P-type semiconductor.

9) Variation of fermilevel with temperature and acceptor concentration in P-type semiconductor.



- At 0K, the fermi level is exactly at the middle of E_v & E_a
- As temperature increases, more and more acceptor atoms gets ionized. So, the number of holes in V.B increases.
- At high temperature, more electron-hole pairs are generated and the material becomes intrinsic.
- At high temperature, the fermi level gradually moves upward and reaches at the middle of E_v & E_c.
- The diagram shows that, the rise of fermilevel from E_f to E_F is slow in case of higher acceptor concentration than lower with the increase of temperature.

Variation of Carrier concentration with temperature in Extrinsic Semiconductor



1. The variation of carrier concentration with temperature in intrinsic semiconductor is shown in the diagram.

2. There are 3 different temperatures Range in it.

3. At 0K, the semiconductor has some charge carriers due to structure property.

4. As the temperature increases, donor atoms gets ionized. So, the number of electrons in CB increases until all the donor atoms gets ionized. This temperature range is called "Impurity Range".

5. At room temperature, the electrons in C.B remains constant over a range of temperature which is called "Exhaust range".

6. As the temperature increased further, the bonds are broken and the electron-hole pairs are created.

7. Hence, more and more electrons are excited to C.B to empty the donor level. Now, the fermilevel shifts to middle of E_g.

8. Now, the material becomes intrinsic and the temperature range is called "Intrinsic Range".

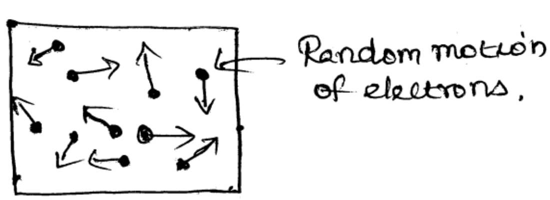
9. The dotted line represents holes concentration and the continuous line represents electrons concentration variation with temperature in Extrinsic Semiconductor".

Carrier Transport in Semiconductors

1. In semiconductors, electrons and holes are called "charge carriers".
2. These charge carriers moves from one point to another point. The movement of these charge carrier is called "Carrier Transport".
3. When an electric field is applied to the charge carriers, they move with a velocity called "drift velocity" and reaches a steady state.
4. In n-type semiconductor, electrons are majority carriers. So when an electric field is applied, the electrons move to +ve terminal of the Battery.
5. In p-type semiconductor, holes are majority carriers. So when an electric field is applied, the holes move to −ve terminal of the Battery.
6. There are 3 types of motion for electrons in the semiconductors. They are (i) Random motion
(ii) Drift motion
(iii) Diffusion motion

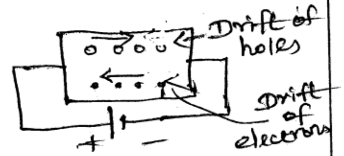
(i) Random Motion

Without electric field, the free electrons move in all direction in a random manner in the semiconductor. This motion is called "Random Motion". So the total velocity in any particular direction is zero.



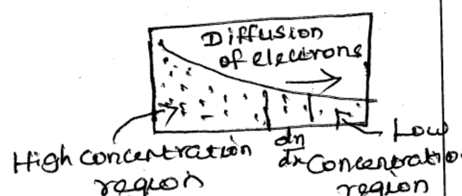
(ii) Drift motion and Drift Current

When the charge carriers are forced to move in a same direction due to electric field, then it is called "Drift motion" and the current is called "Drift Current".



(iii) Diffusion motion and Diffusion current

When the charge carriers move from the Higher concentration region to the lower concentration region, then the motion is called "Diffusion motion" and the current is called "Diffusion current".



7. The drift current density in a intrinsic semiconductor } $J = n_i e(\mu_n + \mu_p)E$

In n-type semiconductor $J_n = ne\mu_n E$

In p-type semiconductor $J_p = pe\mu_p E$

Where, μ_n, μ_p = Mobility of electrons, holes

n, p = Number of electrons, holes

e = charge of electron

E = Electric field

8. The diffusion current density in a intrinsic semiconductor } $J \propto \frac{dn}{dx} e$ (ie) $J = D\left(\frac{dn_i}{dx}\right)e$

So, the diffusion current density of electrons through unit area } $J_n = D_n\left(\frac{dn}{dx}\right)e$

{ Where, D_n = Diffusion constant for electrons

Illy the diffusion current density of holes through unit area } $J_p = -D_p\left(\frac{dp}{dx}\right)e$

D_p = Diffusion constant for holes. }

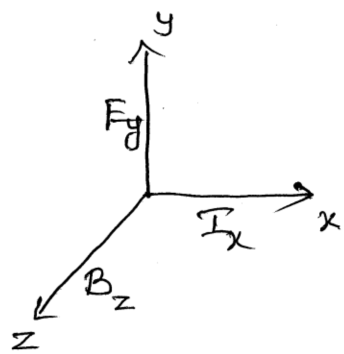
HALL EFFECT

Statement:

When a current carrying conductor is placed in a tranverse magnetic field, then the electric field is produced $\perp^r$ to the direction of current and magnetic field.

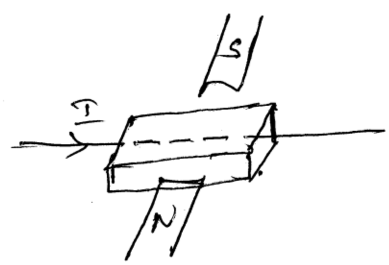
Explanation:

When a current is passed through a conductor along 'x' direction and magnetic field is applied along 'z' direction, then the electric field is produced along 'y' direction.

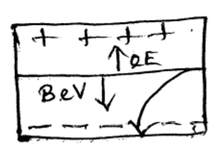


Theory of Hall effect (Hall theory)

1. Let us consider an n-type semiconductor.
2. Let 'I' be the current passed through the semiconductor along x axis.
3. Let 'B' be the magnetic field applied to it along z axis as shown in the fig



4. In general, without magnetic field, the electrons moves from right end to left end of the semiconductor.
5. But after applying magnetic field, the electrons moves downwards direction due to magnetic force.
6. So, large number of electrons are accumulated at the bottom of semiconductor and holes are accumulated at the top of semiconductor.



7. The electric force acting on holes in the upward direction $= eE$
The magnetic force acting on electrons in the downward direction $= BeV$

At equilibrium, $\not{e}E = B\not{e}V$

$$E = BV \quad \text{--- (1)}$$

8. We know, Current density $J = neV$

$$\therefore V = \frac{J}{ne} \quad \text{--- (2)}$$

Sub eqn (2) in (1)

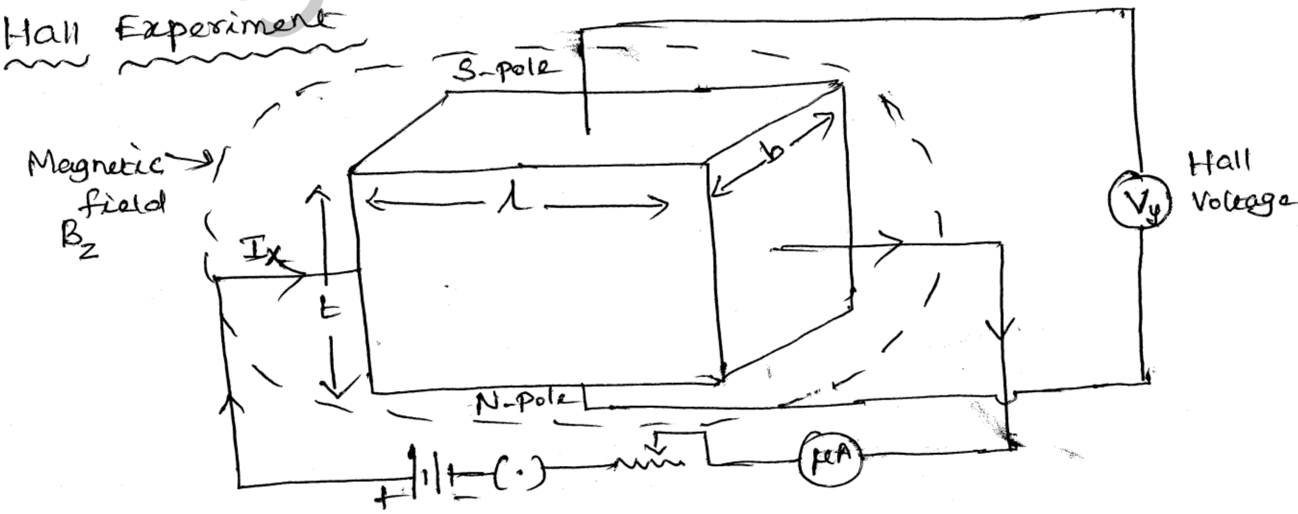
$$E = B \cdot \frac{J}{ne}$$

$$\frac{E}{BJ} = -\frac{1}{ne} = R_H .$$

(i.e) $R_H = -\frac{1}{ne}$ is called Hall Coefficient for electrons

9. Ill^{ly} for P-type semiconductor, the Hall coefficient for holes can be written as $R_H = +\frac{1}{pe}$

Hall Experiment



1. Let us consider a rectangular material of length 'l', breadth 'b' and thickness 't'.
2. A battery, key, rheostat and Ammeter all are connected in series along 'x-axis' of the material.
3. A magnetic field is given to the material along z-axis.
4. To measure the electric field, a voltmeter is connected to the top and bottom face of the material with wires.

Electric field developed along y-direction $E_y = \frac{V_y}{t}$ —— (1)

But, According to Hall theory, $\frac{E_y}{B_z J_x} = R_H$

$$\therefore E_y = R_H B_z J_x \quad \text{—— (2)}$$

eqn (1) = (2)

$$\frac{V_y}{t} = R_H B_z J_x.$$

$$V_y = R_H B_z J_x t$$

But, $J_x = \frac{I_x}{bt}$ $\therefore V_y = R_H B_z \frac{I_x}{bt} t$

(i) Hall voltage $V_y = \frac{R_H B_z I_x}{b}$ (or) $V_y = -\frac{1}{ne}\frac{B_z I_x}{b}$

$\left\{\because R_H = -\frac{1}{ne}\right\}$

(ii) Hall coefficient $R_H = \frac{V_y b}{B_z I_x}$

(iii) Carrier concentration $n = \frac{-B_z I_x}{V_y e b}$

(iv) We know,

$$\sigma = ne\mu$$

$$\mu = \frac{\sigma}{ne}$$

$$\mu = \sigma R_H$$

Mobility $$\boxed{\mu = \frac{\sigma V_y b}{B_z I_x}}$$

(v) Conductivity $$\sigma = \frac{\mu}{R_H} = \frac{\mu}{V_y b / B_z I_x}$$

$$\boxed{\sigma = \frac{\mu B_z I_x}{V_y b}}$$

Applications of Hall effect

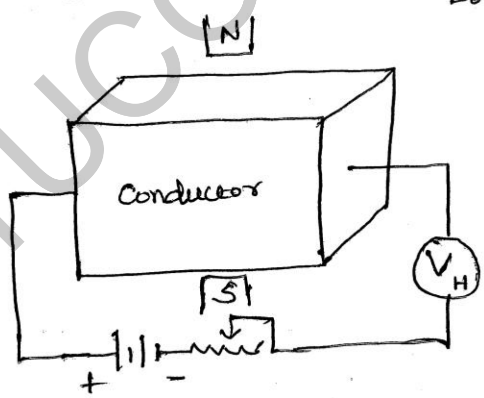
1. It is used to identify the n-type, p-type semiconductors or insulator or conductor
2. It is used to find the Hall voltage, Hall coefficient of material.
3. It is used to find carrier concentration, mobility and conductivity of the material.
4. It is used to design magnetic field meters on the basis of Hall voltage.

Hall Devices

1. The device which is used for Hall effect applications is called "Hall Devices".
2. There are 3 types of Hall devices
   (i) Gauss meter
   (ii) Electronic multiplier
   (iii) Electronic wattmeter

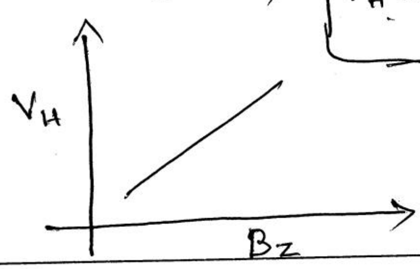
(i) Gauss meter

1) It is a device which is used to measure the magnetic field.
2) Let us consider a current carrying conductor placed in a transverse magnetic field. Then voltage is developed ⊥r to both current and magnetic field.



V_H = Hall Voltage
B_z = Magnetic field along Z axis.

3) The hall voltage (V_H) developed in the material is directly proportional to change in magnetic field. $V_H \propto B_z$
4) So, the change in magnetic field is measured in terms of change in voltage. (ie) $V_H = \frac{R_H B_z I_x}{b}$

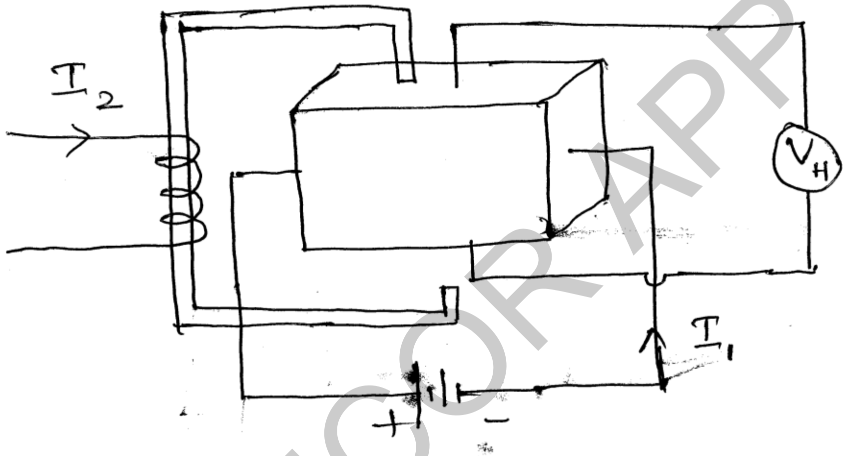


Where,
R_H = Hall coefficient
I_x = Current along x-axis
b = Breadth of material.

(ii) Electronic Multiplier

1) It is a device which is used to measure the product of 2 currents in the materials.

2) By measuring the Hall voltage, the product of currents in the circuit can be measured.



3) Hall voltage $V_H = \frac{R_H B_Z I_1}{b}$

(or) $V_H \propto B_Z I_1$

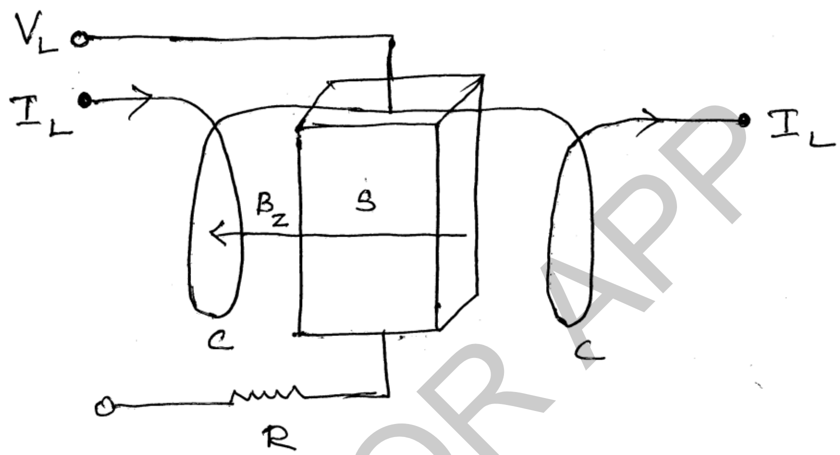
But, Magnetic field (B_Z) is proportional to the current (I_2).

$\therefore V_H \propto I_2 I_1$

(ie) V_H is the measure of product of 2 currents.

(iii) Electronic Wattmeter

1. It is a device which is used to measure the electric power dissipated in a circuit.



2. Let us consider a sample material (S) is placed in a magnetic field produced by load current (I_L) passing through the coils CC.

3. The voltage across the load drives the current (I_y) through the sample. Since $I_y << I_L$

4. The measured Hall voltage is $V_H \propto B_z I_y$

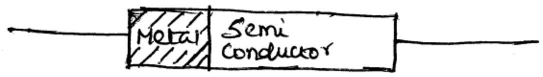
But, $B_z = I_L$

& $I_y = V_L$

$$\therefore \boxed{V_H \propto I_L V_L}$$

Ohmic contacts

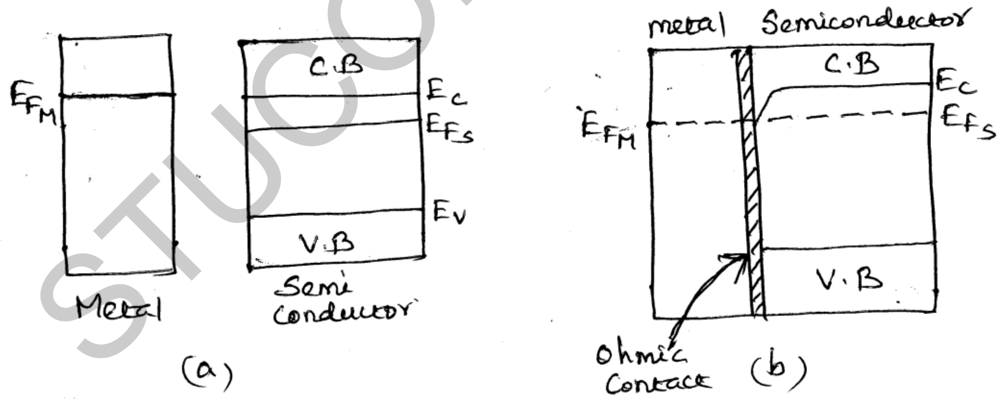
1. Ohmic contact is a type of metal – Semiconductor formed by a contact of metal and heavily doped Semiconductor.



2. It is a non rectifying contact which obey's Ohms law (ie) $V = IR$.

3. The resistance of ohmic contact should always be low and the conductivity should be large.

4. Let us consider a metal and semiconductor which have different Fermi energy values E_{F_M} & E_{F_S} as shown in the diagram (a).

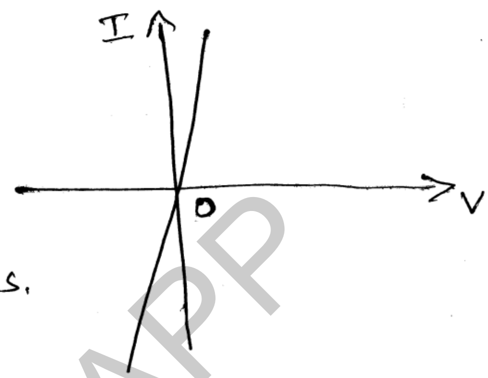


5. When the metal and Semiconductor are made to contact with each other, the energy band of Semiconductor bends downwards near the contact as shown in the diagram (b).

6. It means electrons move from the metal to the empty states in C.B of Semiconductor.

7. The fermi level becomes equal and causes high conductivity at the junction. So, the current is conducted equally in both directions and there is a little voltage drop across the junction.

8. In ohmic contact, the current is directly proportional to the Voltage across the junction. This is studied by V-I characteristic curve as shown in the graph.

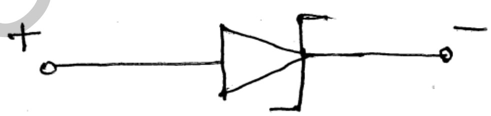


9. Applications:

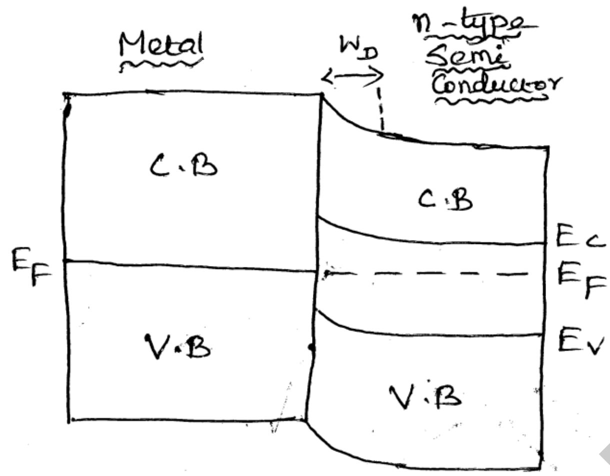
The ohmic contacts are used to connect semiconductors, IC's and to external terminals.

Schottky Diode

1. Schottky diode is a biasing device which is formed using metal and n-type semiconductor.
2. In this diode, the metal has higher work function value than n-type semiconductor. So, the current flows from metal to n-type semiconductor in one direction.



3. In Schottky diode, the fermilevel of semiconductor is higher than the metal. So, the electrons in C.B of semiconductor moves to empty energy levels above the fermilevel of metal.
4. So, it creates contact potential at the junction and creates +ve potential at the semiconductor side.



5. After the contact, the depletion region increases in the semiconductor and causes bending of energy bands on the semiconductor side.

6. The contact potential formed at the junction prevents further movement of electrons between metal and semiconductor.

- This is called "Schottky Barrier".

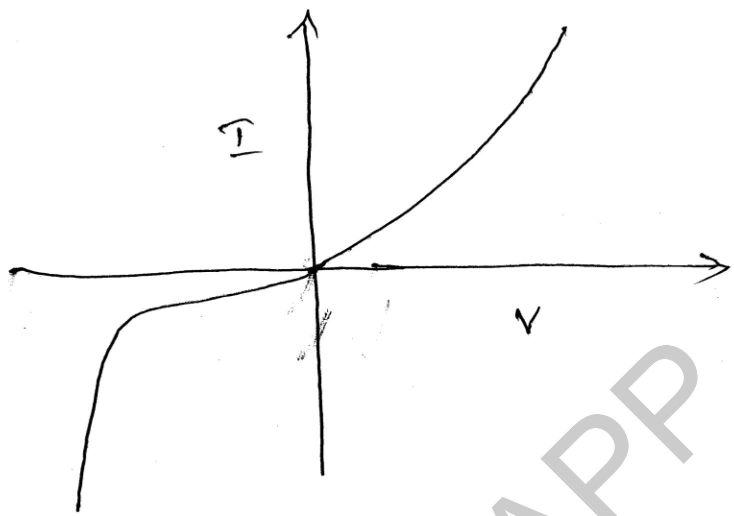
7. The inbuild potential (V_0) at the Schottky junction can be written as the difference in work function of metal and semiconductor.

$$eV_0 = \phi_m - \phi_{semi}$$

8. If Schottky diode is forward biased, the external potential opposes the inbuild potential. So, the electrons are injected in to n-type semiconductor externally.

- So, the current increases with the increase of external potential.

9. If Schottky diode is reverse biased, the external potential applied in the same direction of inbuild potential. So, the width of depletion region further increased and there is no flow of electrons from the semiconductor to metal.



V-I characteristic Curve of Schottky Diode.

Advantages

- It has low capacitance value
- Easily changes to ON-OFF State
- Requires very small voltage to produce large current
- Less noise, High efficiency
- operates at High frequencies

Applications

- It can be used as rectifier
- used in RF applications
- used in power supplies
- used in logic circuits, sensors
- used in communication receivers like radars.
- used in clipping, clamping and computer gating.

MAGNETIC PROPERTIES OF MATERIALS

Basic terms

1. Magnetic dipole moment (M)

A system which consists of 2 equal and opposite magnetic dipoles seperated by a distance is called "Magnetic dipole moment".

$$\boxed{M = m \times 2l}$$

Where, m = pole strength
l = Length of magnet

It is also defined as the current flowing through a circular wire of area 'a'. (ie) $\boxed{M = I a}$

2. Magnetic field

The space around the magnet is called "Magnetic field".

(or) The number of lines of forces (Flux) passing through the material is called magnetic induction (B).

3. Magnetic field intensity (H)

The force experienced by the unit north pole placed at that point in a magnetic field is called magnetic field intensity.

4. Magnetic permeability (μ)

The ratio between magnetic induction and magnetic field intensity is called "Magnetic permeability".

$$\boxed{\mu = \frac{B}{H}}$$

It is a measure of magnetic field penetration in the material.

5. Relative Permeability (μ_r)

It is the ratio between permeability of medium and permeability of free space.

$$\boxed{\mu_r = \frac{\mu}{\mu_0}}$$

6. Intensity of magnetisation (I)

The magnetic dipolemoment per unit volume of the material is called "Intensity of magnetisation".

7. Magnetic Susceptibility (χ)

The ratio between intensity of magnetisation and magnetic field intensity.

$$\boxed{\chi = \frac{I}{H}}$$

It is a measure of how easily the material can be magnetised in a magnetic field.

8. Relation between μ_r and χ

We know, $B = \mu H$ (ie) $\mu = \frac{B}{H}$

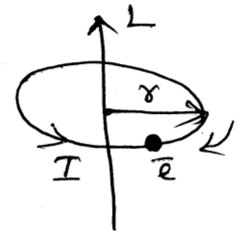
Also $B = \mu_0(I+H)$ $\mu_0 = \frac{B}{I+H}$

$$\mu_r = \frac{\mu}{\mu_0} = \frac{B/H}{B/I+H} = \frac{I+H}{H} = \chi + 1$$

$$\boxed{\mu_r = \chi + 1}$$

Origin of magnetic moment

1. An atom has +ve nucleus and -ve nucleus. So, it can be considered as magnetic dipole.
2. The electron spins itself and also revolves around the nucleus in an orbit.
3. The spin motion of electron is called "Spin magnetic moment" and orbital motion of electron is called "orbital magnetic moment".
4. The orbital motion of electron about nucleus is equal to a small current in a coil.
5. The current at any point in a coil



$$I = \frac{Charge}{Time} = \frac{e}{T} \quad \text{--- (1)}$$

We know,

$$V = r\omega = r(2\pi\gamma) = r\,2\pi\left(\frac{1}{T}\right) \qquad \left\{\omega = 2\pi\gamma,\ \gamma = \frac{1}{T}\right\}$$

$$T = \frac{2\pi r}{V} \quad \text{--- (2)}$$

sub (2) in (1)

$$I = \frac{e}{2\pi r/V} = \frac{eV}{2\pi r} \quad \text{--- (3)}$$

6. The orbital magnetic moment $\mu_L = I \times A$

$$= \frac{eV}{2\pi r} \times \pi r^2$$

$$\mu_L = \frac{eVr}{2}$$

$$\mu_L = \frac{eVrm}{2m}$$

So, orbital magnetic moment $\boxed{\mu_L = \frac{eL}{2m}}$ $\quad \{L = mVr\}$ orbital Angular momentum

Bohr Magneton

The orbital magnetic moment and spin magnetic moment of $\bar{e}$ can be expressed in terms of atomic unit of magnetic moment called "Bohr magneton".

Magnetic moment of electron $\mu_L = \frac{eL}{2m}$

Where

L = orbital angular momentum

$L = n\hbar$ (From Bohr theory)

For ground state $n = 1$

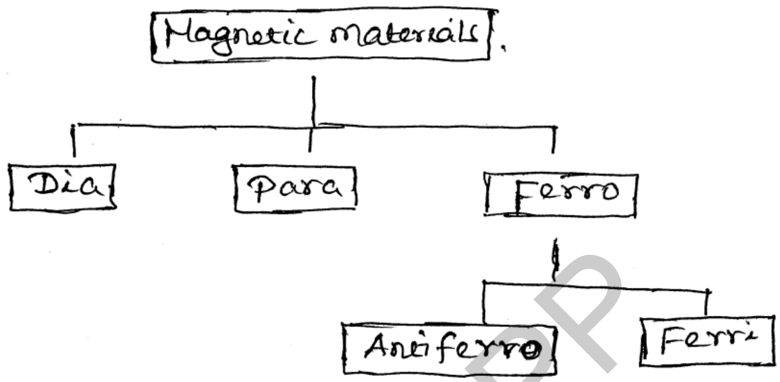
$\therefore L = \hbar$

$\therefore$ Magnetic moment $\mu_L = \frac{e\hbar}{2m}$

$= 9.27 \times 10^{-24}$ amp-m^2

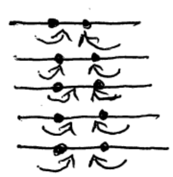
$\mu_L = 1$ Bohr magneton

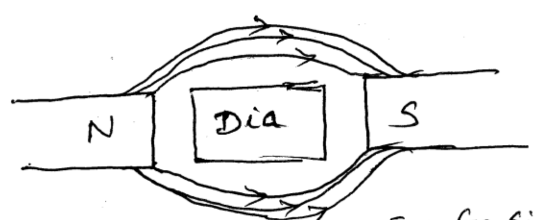
Classification of magnetic materials



(i) Diamagnetic materials

1. Materials which have no permanent dipoles are called "Diamagnetic materials".
2. These materials have even and equal number of electrons which are spinning in opposite direction.
3. So, the net magnetization is zero in each atom of the material.
4. When an external magnetic field is applied, the magnetic flux are repelled by the diamagnetic materials.





Eg: Ge, Si, organic & Alkali materials

5. All the dipoles are aligned ⊥r to the direction of applied magnetic field.
6. The permeability is less than 1 and the susceptibility is –ve for these materials. ($\chi = \frac{C}{\theta}$) where C = Curie constant, θ = Curie Temperature
7. At temperature $T < T_c$, the diamagnetic materials become normal materials.

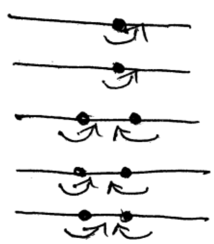
(ii) Paramagnetic material

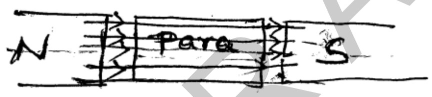
1. Materials which have permanent dipoles are called "Paramagnetic materials".

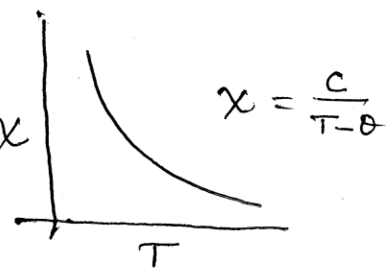
2. These materials have some unpaired electrons in every atom.

3. So, the net magnetic moment is not zero.

Eg: Na, K, Cr.. etc.







4. When an external magnetic field is applied, the magnetic flux are attracted by the material.

5. All the dipoles are aligned ||le to the direction of applied magnetic field.

6. The permeability value is greater than 1 and susceptibility of the material is +ve, $\chi = \frac{C}{T-\theta}$ where, T = Temperature, θ = curie temperature

7. At temperature $T < T_c$, the paramagnetic material becomes diamagnetic material.

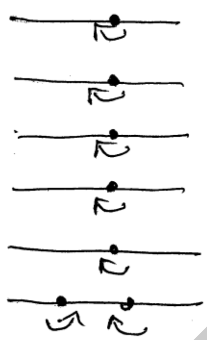
(iii) Ferromagnetic materials

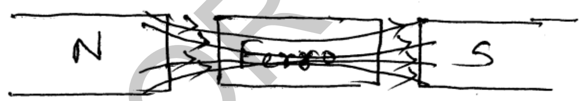
1. Materials which have large number of permanent dipoles are called "Ferromagnetic materials".

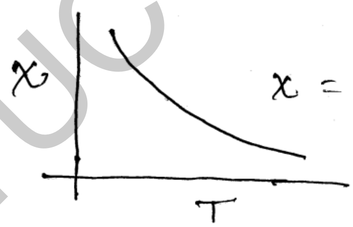
2. These materials have more number of unpaired electrons in every atom.

3. So, the net magnetic moment is not zero.

   Eg: Fe, Co, Ni..etc.







$$\chi = \frac{C}{T \pm \theta}$$

4. When an external magnetic field is applied, the magnetic flux are strongly attracted by the material.

5. All the dipoles are aligned $\parallel^{le}$ to the direction of applied magnetic field.

6. The permeability is very much less than 1 and susceptibility is $+^{ve}$

   (ie) $\chi = \frac{C}{T \pm \theta}$

8. At temperature $T > T_c$, the ferromagnetic material becomes paramagnetic material.

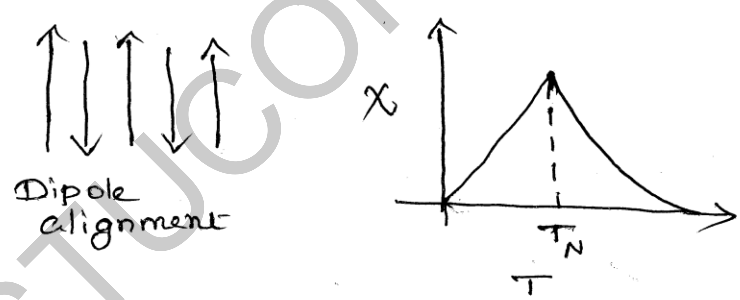
(iv) Antiferro magnetic materials

1. The materials which have permanent dipoles in AntiParallel direction with same magnitudes (values) are called Antiferro magnetic materials.

2. The net magnetic moment is 0.

   Eg: FeO, MnO, Cr_2O_3 ...etc.

3. When external magnetic field is applied, the magnetic flux are repelled by the material.



4. The permeability is very much less than 1 and susceptibility is +ve.

5. With the increase of temperature, the susceptibility (χ) is increased up to a particular temperature called "Neel Temperature". (T_N).

6. Above the Neel Temperature (T_N), the susceptibility decreases.

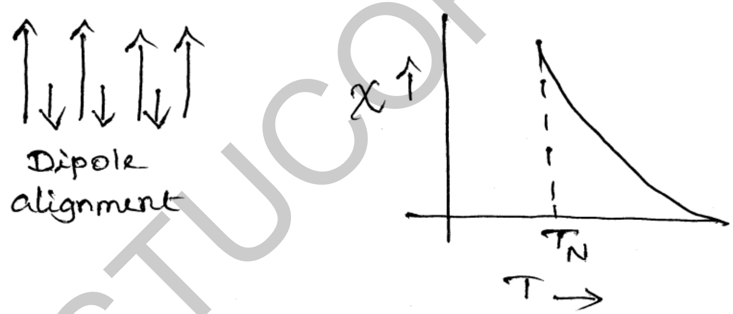
(V) Ferrimagnetic materials

1. Materials which have permanent dipoles in antiparallel direction with different magnitudes (values) are called "Ferrimagnetic materials".

2. The net magnetic moment is not zero.

   Eg: Ferrous ferrite, Nickel Ferrite ...etc.

3. When an external magnetic field is applied, the magnetic flux are attracted by the material.



4. The permeability is greater than 1 and susceptibility is +ve and very large.

5. Above the Neel temperature, the susceptibility decreases.

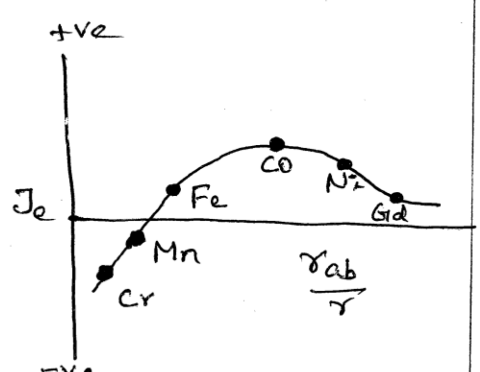
Origin of Ferromagnetism and Exchange Interaction

1. The ferromagnetic materials like Fe, Co, Ni shows high degree of magnetisation when magnetic field is applied.
2. Even in the absence of magnetic field, they have parallel alignment of dipoles. ↑↑↑↑
3. It is not due to magnetic interaction. But due to exchange interaction between electron energy.
4. The exchange interaction between any 2 atoms depends upon the interatomic distance and spin values of outer electrons.
5. The exchange interaction between any two atoms is given by

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

where,
J_e = Exchange integral
S_1, S_2 = Spin angular momentum of two electrons

6. A graph can be plotted for exchange integral (J_e) and the ratio of inter atomic distance to radius of electron orbit.



7. The J_e is $+^{ve}$, when $\frac{r_{ab}}{r} > 3$.

   So, the atoms posses ferromagnetic properties. Eg: Fe, Co, Ni, Gd

8. The J_e is $-^{ve}$, when $\frac{r_{ab}}{r} < 3$.

   So, the atoms posses Antiferromagnetic properties. Eg: Mn, Cr.

r_{ab} = Interatomic distance
r = Radius of $\bar{e}$ orbit

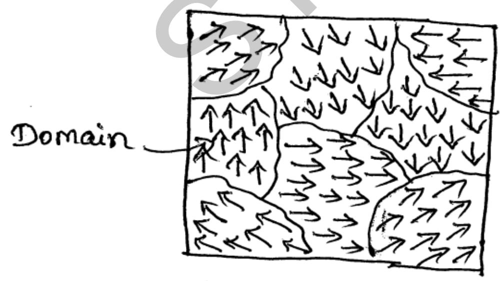
Saturation magnetization and Curie temperature

1. Definition :
   The maximum magnetization in a ferromagnetic materials when all atomic dipoles are aligned is called "Saturation magnetization".
2. When the ferromagnetic material temperature is increased, the lattice (Structure) Vibration becomes more energetic in it.
3. So, there will be different directions of spin of electrons.
4. At a particular temperature, the ferromagnetic behaviour disappears. The temperature is called "Curie temperature".
5. Above the curie temperature, the ferromagnetic material behaves like a paramagnetic material.
6. Hence, the saturation magnetization decreases from maximum value to zero at Curie Temperature.
7. At curie temperature, the thermal energy (kT_c) is enough to overcome the exchange energy (E_{ex}). (ie) $E_{ex} = kT_c$.
8. The magnetic susceptibility of ferromagnetic materials become large which is given by

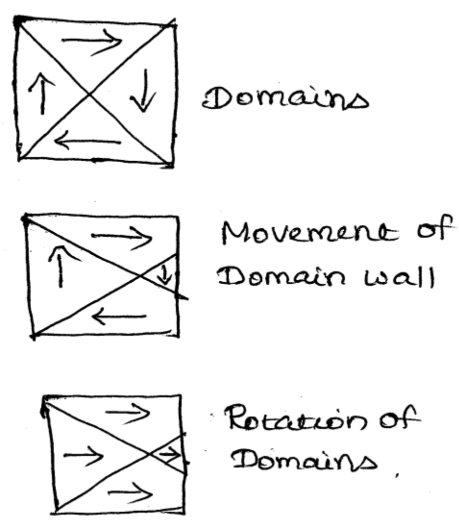
$$\chi = \frac{C}{T - T_c}$$

Domain theory of ferromagnetism

1. The domain theory was explained by the scientist Weiss in 1907.
2. He explained that the ferromagnetic material consist of large number of small regions called "Domains".
3. In all domains, the atomic dipoles are aligned in the same directions.
4. Each domain has dipole moment. But, the direction of magnetization varies from one to another. So, the net magnetic moment is zero.
5. There are 2 process takes place in ferromagnetic material when magnetic field is applied to it. (i) Movement domain wall
(ii) Rotation of domains
6. If weak magnetic field is applied, there will be a movement of domain wall.
7. If strong magnetic field is applied, there will be a rotation of domains.



Ferro magnetic material



8. When a magnetic field is applied to ferromagnetic materials, 4 different types of energies stored in it.

(i) Exchange Energy

It is due to interaction between the spinning of electrons. It makes the dipoles align $\parallel^{le}$ with eachother within the domains.

(ii) Anisotropy Energy

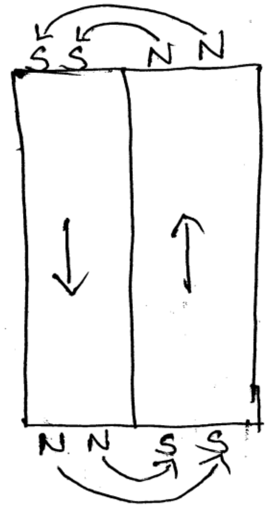
The excess energy required to magnetize the material in a particular direction than in easy direction is called "Anisotropy energy".

(iii) Domain wall Energy

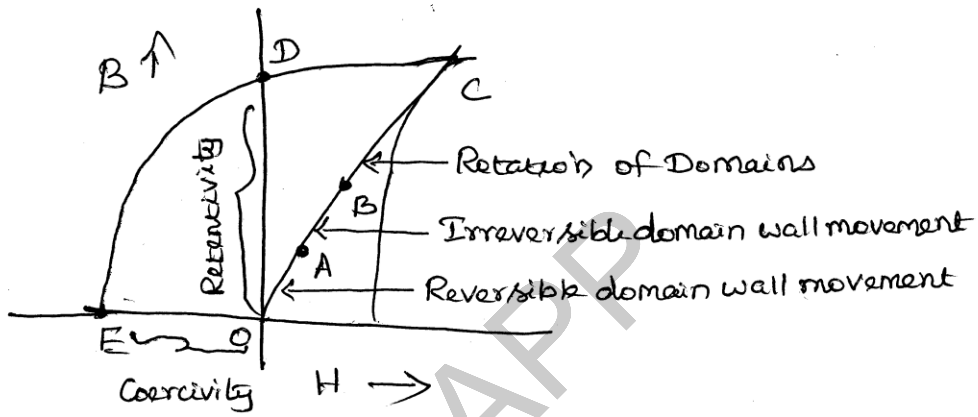
The sum of exchange energy and anisotropy energy in the domain wall is called "Domain wall Energy".

(iv) Magnetization Energy

The change in dimension of ferromagnetic material when magnetic field is applied is called "Magnetostriction Effect". The energy generated in this effect is called "Magnetostriction Energy".



B-H Curve (Hysterisis curve) based on domain theory



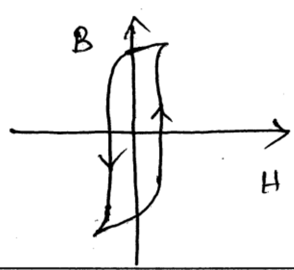
1. When an external magnetic field is applied to a ferromagnetic material, the domain walls move slowly in the direction of magnetic field.
2. When the magnetic field is removed, the domains return back to the original position. This is indicated by 'OA' in the diagram.
3. When the magnetic field is further increased, the domain walls move further. But the movement is irreversible. This is indicated by 'AB' in the curve.
4. When the magnetic field is strong, all the domains rotated in the magnetic field direction. This is indicated by 'BC' in the curve.
5. Once all domains rotated, the material gets saturated. It is indicated by the point 'C' in the curve. The material gets maximum magnetization at this point.
6. This magnetization can be destroyed by applying reverse magnetic field.
7. During reverse magnetic process, the magnetic induction (B) will not be zero even if the magnetic field intensity is zero. This magnetic induction value is called "Retentivity or Residual induction". ∴ It is indicated by 'OD' in the graph.
8. Inorder to make 'B' to zero, a reverse magnetic field is applied which is called "coercivity or coercive field". It is indicated by "OE" in the graph.

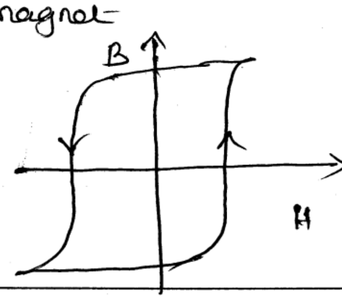
9. If ferromagnetic material is taken through one complete cycle, an hysterisis loop is formed.

10. Some work has to be done for one complete cycle of magnetization and demagnetization of ferromagnetic material is considered to be energy loss. This energy loss is also called as "Hysterisis loss".

Difference Between Soft and Hard magnetic materials

	Soft magnetic material	Hard magnetic material
1.	They can be easily magnetized and demagnetized	They cannot be easily magnetized and demagnetized
2.	Hysterisis loop is very narrow	Hysterises loop is very broad
3.	Hysterisis loss is minimum	Hysterisis loss is maximum
4.	Permeability and Susceptibility is high	Permeability and susceptibility is small
5.	Retentivity and coercivity is small	Retentivity and coercivity is large
6.	Eg: Fe, Si alloys, Ferrites	Carbon steel, Tungsten steel, Chromium steel
7.	It is used to make temporary magnet	It is used to make permanent magnet



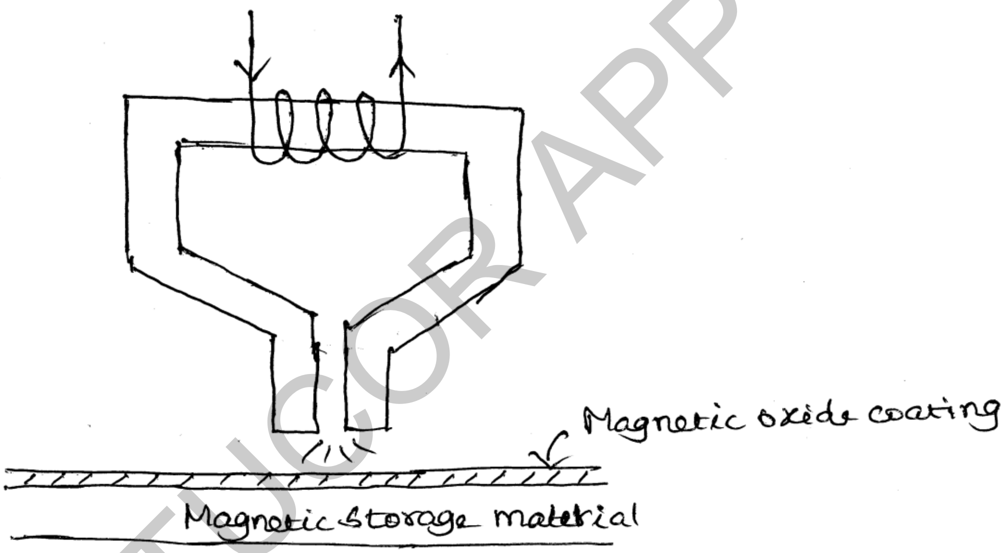


Magnetic principle in computer data storage

1. The magnetic materials are used for writing / Reading the audio and Video signals.
2. They are used as storage devices such as floppy disc, Hard disc.
3. The main part of magnetic storage devices is magnetic writing head and magnetic reading head.
4. The function of the heads are based on the principle of magnetic induction.
5. In general, In ferromagnetic materials, dipoles are aligned $\parallel^{le}$ to eachother. If we apply even a small magnetic field, a large value of magnetization is produced.
6. Using this property, informations are stored as '1's and '0's.
7. The parameters for magnetic writing / reading are
   (i) An electric current through the coil.
   (ii) Soft magnetic material as temporary storage device
   (iii) Hard magnetic material as permanent storage device
   (iv) Magnetic Resistor
8. Writing Mechanism
   - When the magnetic material moves across the write head, the magnetic field generated by the head affects the dipoles on the material.
9. - So, the change in polarity of dipoles in the material is considered as '1' and No change in polarity in the material is considered as '0'.

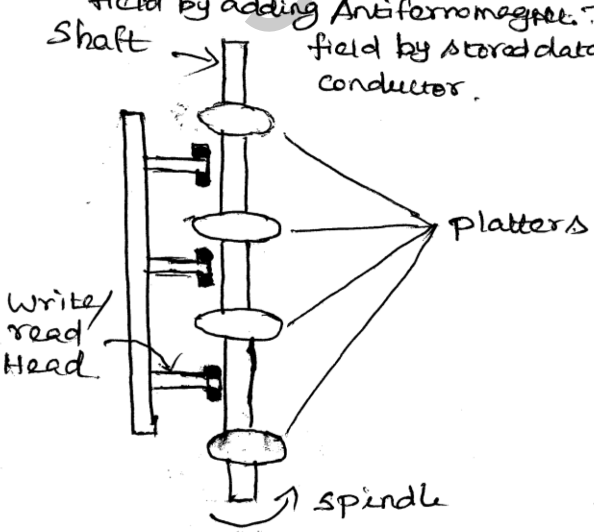
9. Reading Mechanism

- When the recorded material moves over the Read Head, the magnetised spot generates a small electric signal due to EMF.
- So, the corresponding voltage fluctuation is then converted to information signal.

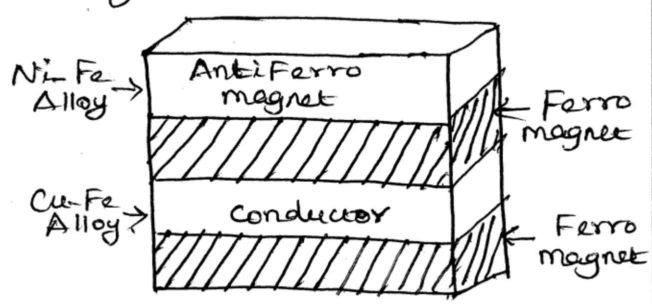


Magnetic Hard disc with GMR Sensor

1. Magnetic hard disc is a magnetically coated data storage device. It is also called "Direct access storage device".
2. It is made up of Hard Aluminium platters (discs) coated with oxides.
3. Each platters are seperated by write/read heads.
4. Many discs are mounted on the vertical shaft forming a disc pack. It is placed in a drive mechanism called "Hard disc drive" (HDD).
5. The Heads used for write/read mechanism is Giant Magneto Resistor" (GMR).
6. This GMR is highly sensitive to change in magnetization on the disc. It is madeup of 4 layers such as 2 ferromagnetic and 1 antiferro magnetic layer. 1 ferromagnetic layer is pinned and another is unpinned. The pinned ferromagnet is not disturbed by magnetic field by adding Antiferromagnet. The unpinned ferromagnet is sensitive to magnetic field by stored data by adding conductor.



(Drive mechanism)



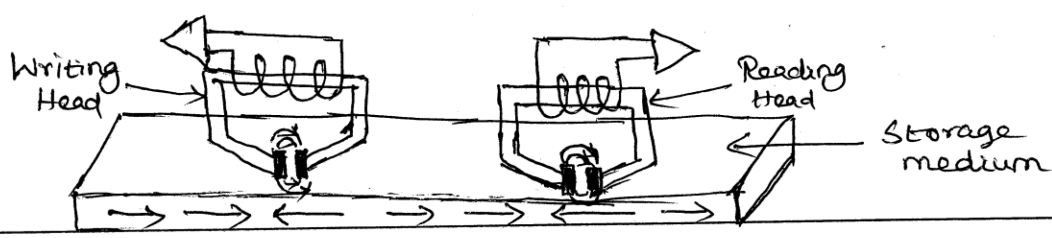
(GMR Head)

7. Writing Mechanism

- In a writing head, a coil is wound around ferromagnet.
- When a current is passed through the coil, a magnetic field is produced between the gaps of the Head.
- This magnetic field affects the magnetic dipoles on the discs and changes the direction of dipoles.
- So the magnetic field affected spot on the disc is considered as Stored or recorded data as '1' and the magnetic field not affected spots is considered as '0'.
- So the information is stored in the form of 1's and 0's on the disc.

8. Reading mechanism

- A reading head is used to read or retreive data from the disc.
- When the reading head is kept near the recorded disc, the resistance of the GMR sensor head changes w.r.t the direction of dipoles.
- When the dipoles are $\parallel^{le}$ to the direction of magnetic field in the head, then the resistance in the GMR is minimum. So, large current flows in it which represents the data as '1'.
- When the dipoles are $\perp^{r}$ to the direction of magnetic field in the head, the resistance in GMR is maximum. So, small current flows in it which represents the data as '0'.
- So, with the help of reading current, 0's and 1's can be retrieved from the hard disc using GMR sensor head.



Optical Properties of materials

Classification of optical materials

optical materials are generally classified in to 3 types.
They are (i) Transparent materials
(ii) Translucent materials
(iii) Opaque materials

(i) Transparent materials

The materials which transmits the light with little absorption and reflection are called "Transparent materials". In this material, we can view the object clearly through it.
(Eg) Some Semiconductors, Electrically insulated materials.

(ii) Translucent materials

The materials which scatters the light within the medium so that the diffused light is transmitted to the other side of the material is called "Translucent materials".
In this material, we can view the object.

(iii) Opaque materials

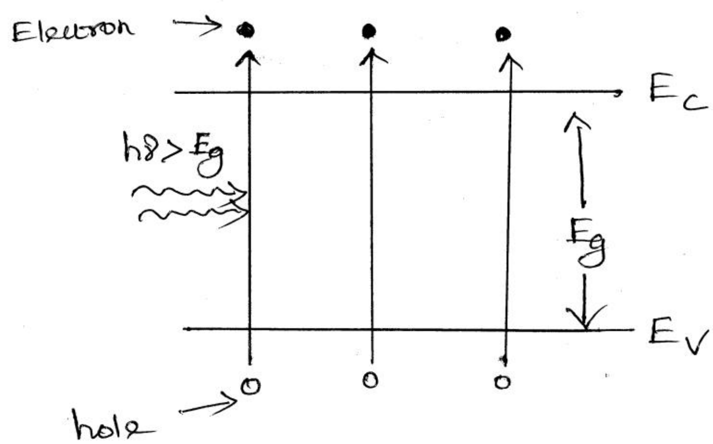
The materials which absorbs the light is called "opaque materials". When all wavelengths of visible light incident on this material, either it gets reflected or absorbed.

Carrier Generation and Recombination process

1. Carrier generation is the process where the electrons and holes are created.
2. Recombination is the process where the electrons and holes are disappeared.
3. There are 3 types of carrier generation. They are
   (i) photogeneration
   (ii) phonon generation
   (iii) Impact ionization

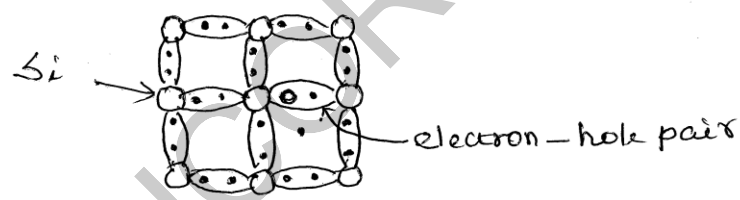
(i) Photogeneration

- In photogeneration, a light of frequency 'ν' falls on the Semiconductor.
- If the energy of light ($h\nu$) is greater than Energy gap (E_g) of semiconductors, they absorbs light.
- Then the electrons jumps from V.B to C.B by generating electron-hole pair.



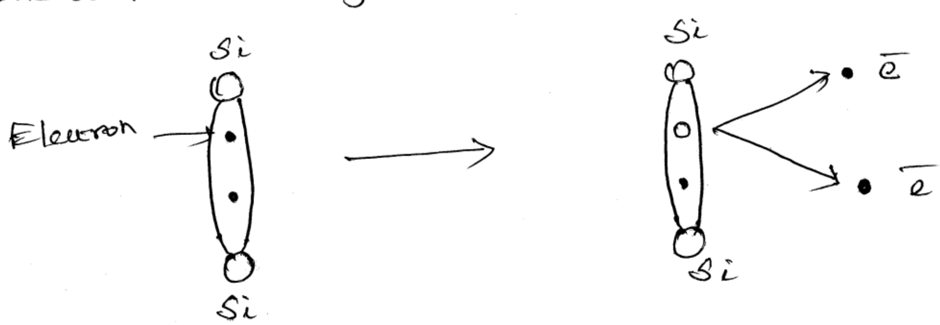
(ii) Phonon generation

- The phonon generation occur when heat energy is given to the Semiconductor.
- With the increase of temperature, the structure vibration in the Semiconductor increases and Covalent Bonds are broken.
- Then the electron-hole pairs are generated.



(iii) Impact Ionization

- The impact ionization occurs when an electric field is applied to the semiconductor.
- The electrons gain the energy from electric field and hits the atom.
- In this process, covalent bonds break out and generates more and more charge carriers.

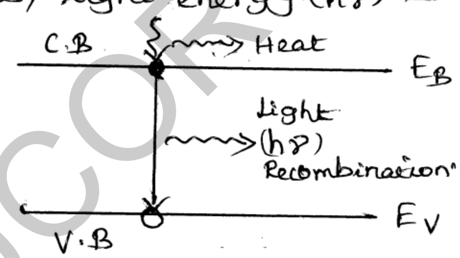


4. There are 3 types of Recombination. They are

(i) Radiative recombination
(ii) Shockley - Read-Hall Recombination
(iii) Augur Recombination

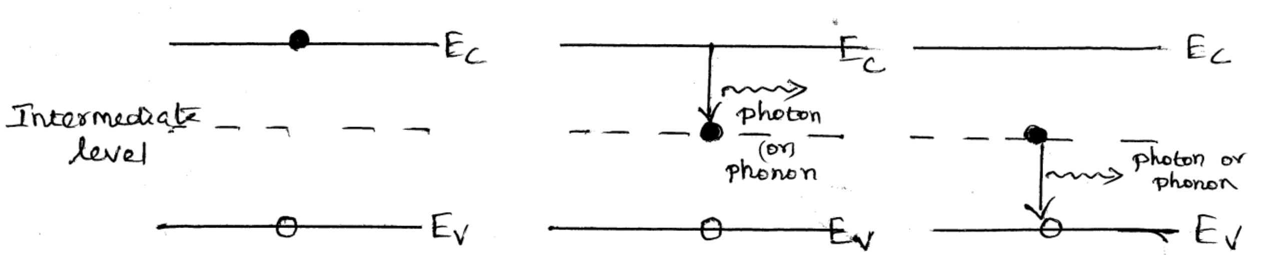
(i) Radiative Recombination.

It occurs in directbandgap Semiconductors like Ga-As.
In this process, electrons from C.B minimum falls to V.B maximum
In this process, light energy (hν) is emitted.



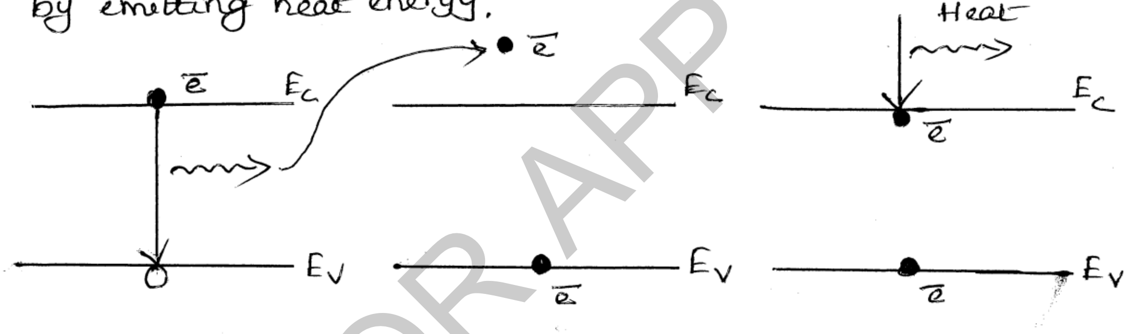
(ii) Shockley - Read - Hall Recombination

In this process, the electrons from C.B minimum comes to intermediate defect level between E_C & E_V by radiating energy as photons or phonons. It occurs in impure Semi-conductor.



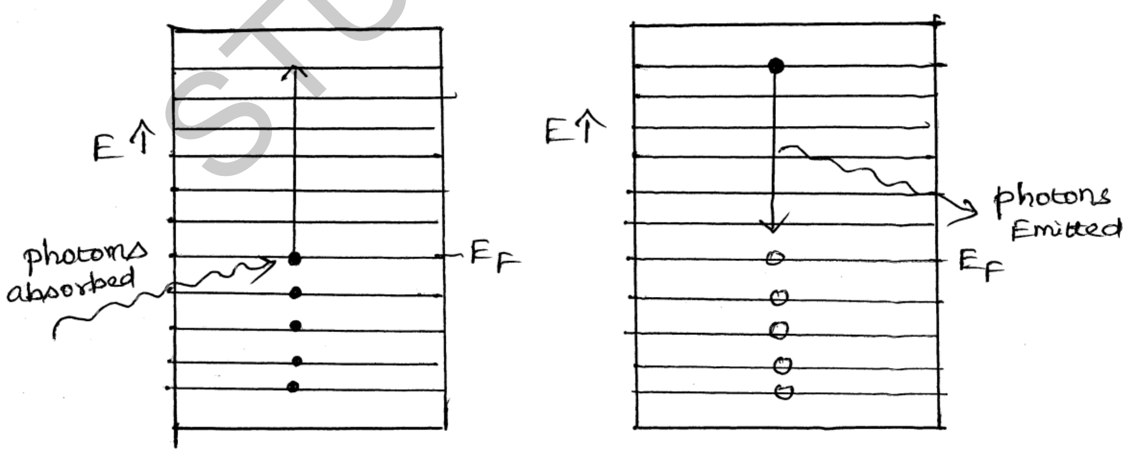
(iii) Augur Recombination

In this process, energy radiated during the recombination of electron and hole is given to 3rd free electron in the C.B. Then, this 3rd excited electron comes back to the C.B by emitting heat energy.



Absorption and Emission of light in Metals

1. Most of the metals are non-transparent or opaque to the light radiation.
2. When a light energy falls on the opaque material, then it get absorbed.
3. Metals are non transparent to EMW from Radio waves to UV rays. But transparent to X-rays and γ-rays.
4. Most of the absorbed light radiation is Re-emitted from the surface as visible light with same wavelength.
5. So the emitted light appears as reflected light.



Absorption and Emission of light in Semiconductors

1. When a light is allowed to fall on the electrons in V.B of semiconductor, they gets absorbed.

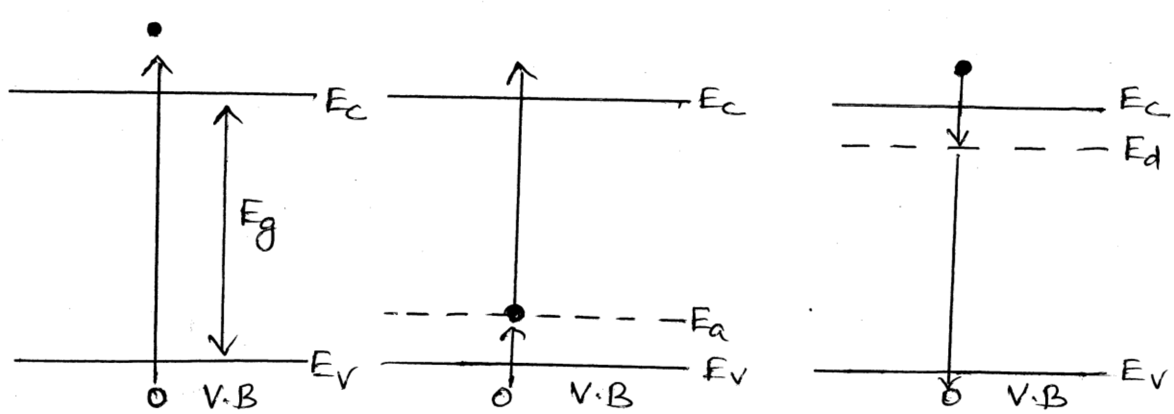
2. Then the electrons gets excited and moves from V.B to C.B through band gap (E_g).

3. The electrons gets excited only if the energy of light photon is greater than Band gap of semiconductor. (i.e) $h\nu > E_g$.

4. The maximum wavelength for visible light is λ_{max}. So, the minimum energy gap (E_g) for absorption to the semiconductor is $E_{g(min)} = \frac{hc}{\lambda_{max}} = 1.8\, eV$.

5. It shows that, the visible light is absorbed by the semiconductor having $E_g < 1.8\, eV$.

6. In extrinsic semiconductors, acceptor and donor impurities creates a new energy levels called acceptor level (E_a) and donor level (E_d) within the bandgap.



7. A particular wavelength of light may be absorbed and the electrons are excited from one of these impurity level within the band gap.

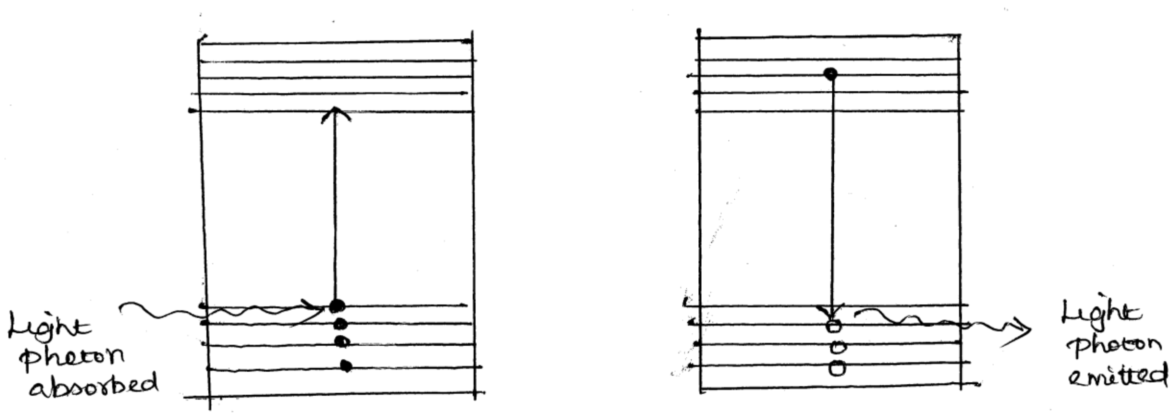
Absorption and Emission of light in insulators

1. Absorption of light in insulators occur when the electrons are excited from V.B to C.B through Energy gap (E_g).
2. In this transition holes in V.B and electrons in C.B are created.
3. The absorption of light in insulator occur only if energy of light is greater than bandgap. (ie) $h\nu > E_g$. (or) $\frac{hc}{\lambda} > E_g$

$$\therefore E_{g(max)} = \frac{hc}{\lambda_{min}} = 3.1\ eV$$

where,
c = velocity of light
h = planks constant
λ = wavelength of light

4. If Bandgap (E_g) of light is greater than 3.1 eV, then there is no absorption of light. But, there will be an excitation of electrons from V.B to C.B.



P-N - Junction Diode

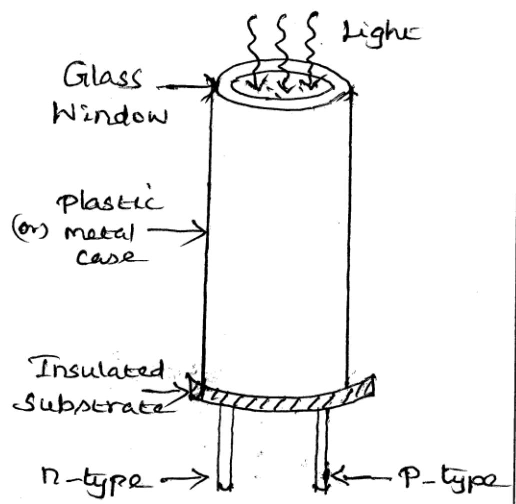
Principle:

When a p-n junction diode is exposed to light under reverse bias, it produces electron-hole pairs. Due to the flow of these charge carriers, it produces reverse current.

Construction:

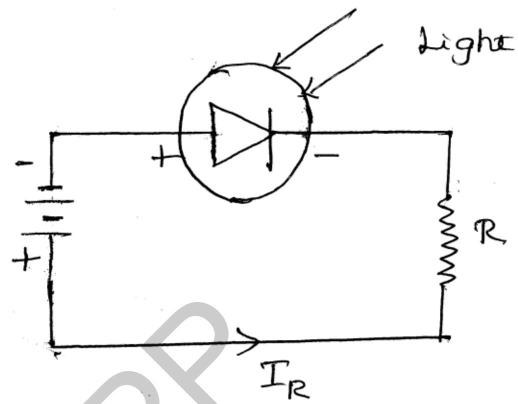
1. The photo diode is made up of n-type material and P-type material placed in a transparent plastic (or) metal case.
2. A small glass window is provided on the top so that the light pass through it and falls on p-n junction.
3. The p-n junction is kept on a insulated substrate (base) material.

Working:



1. Initially, the photo diode is reverse biased and no light is incident on the p-n junction
2. So, a very little reverse current (I_R) flows through the circuit. This current is called "Dark current".
3. When the light is allowed to incident on the p-n junction, then each photon creates an electron-hole pair at the junction.

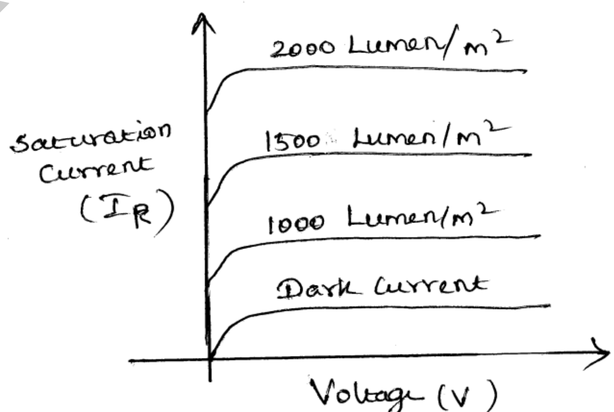
4. The photogenerated charge carriers diffuse to p-n junction and provides additional current called "photo current".



5. The photo current increases with increase in intensity of light falling on the p-n junction.

6. The current reaches the maximum is called "Saturation current".

7. The V-I characteristics curve is shown in the diagram.



Advantages:

1. Light weight, compact
2. Long life period.
3. Low noise
4. Wide spectral range of response

Disadvantages:

1. Dark current is dependent on temperature
2. Poor efficiency in rain/winter seasons.
3. Amplification Required.

Applications:

1. It is used in CCD
2. It is used in Radio, Camera, clocks, Street lights ... etc.
3. It is used in CD player, TV remote control
4. It is used in "Light operated switches".
5. It is used in medicine in CT scans.

Solar cell

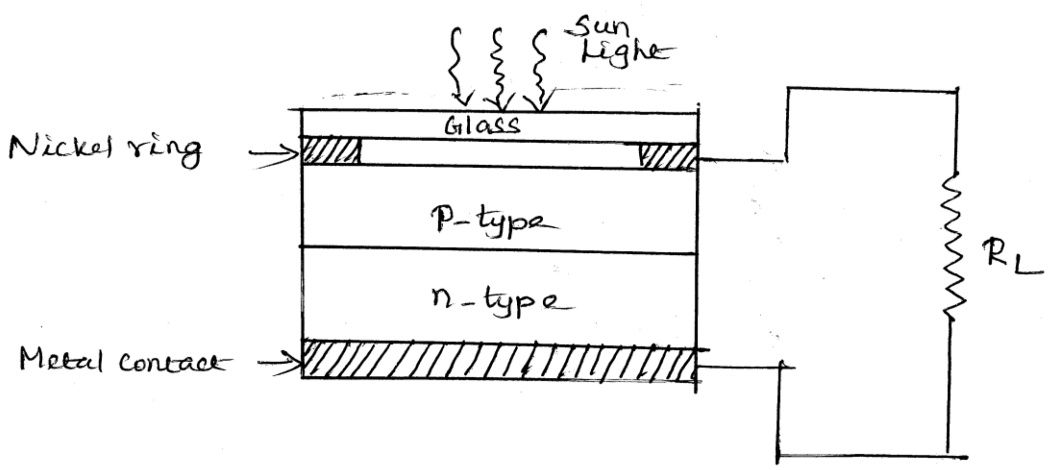
Solar cell is a p-n junction diode which converts light energy into electrical energy.

Principle

When light energy from the sun falls on large area of photo-diode, it directly converts light energy into electrical energy with large efficiency.

Construction

1. A solar cell is made up of p-type and n-type materials.
2. The thickness of n-region is made small so that, the charge carriers ($\bar{e}$ & holes) generated during its operation and diffuses in to p-n junction.
3. Both P & n type materials are connected to load resistance (R_L) through ohmic contacts.
4. The nickel ring is provided at the top of p-region with glass surface and the metal is provided at the bottom of n-region that acts as ohmic contact.



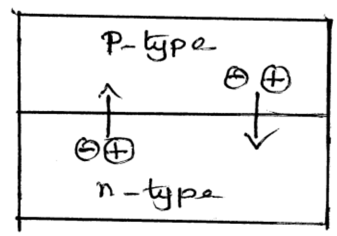
Working

1. When light radiation from the Sun falls on p-n junction diode, the photons excite the electrons and generates electron-hole pair.

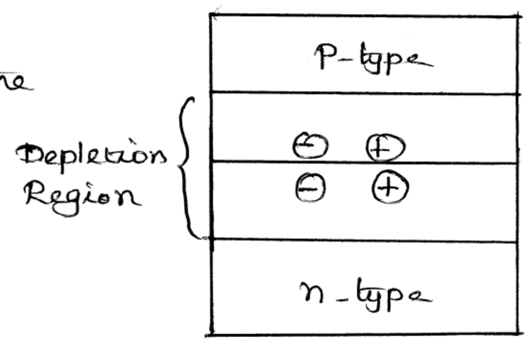
2. These electrons and holes quickly diffuses and reaches the depletion region of p-n junction.

3. Now, Due to strong barrier field, the minority electrons from p-region moves towards n-region and minority holes from n-region moves towards p-region.

4. So, both electrons and holes are accumulated on both sides of p-n junction which produces open circuit voltage.



5. If Load resistance is connected across the diode, then reverse current (I_R) flows through the circuit.



Advantages:

1. It is pollution free device.
2. Long life and durable.
3. It saves electricity

Disadvantages:

1. Installation cost is high.
2. Solar panels occupy more space.

Applications:

1. It is used for the production of electricity to our daily needs.
2. It is used in calculators, watches, Street lights etc.
3. It is used in Satellites and Space Vehichles.

Light Emitting Diode (LED)

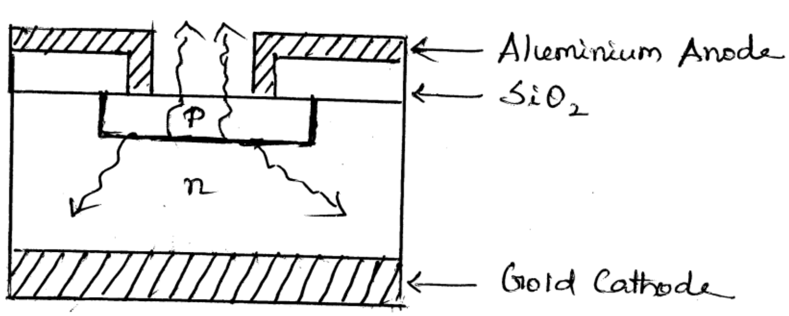
It is a p-n junction diode which emits light when it is forward Biased.

Principle:

When a p-n junction semiconductor diode is forward biased, electrons from n-region are injected to p-region and holes from p-region are injected to n-region. At the p-n junction, electrons and holes are recombined and light photon is emitted.

Construction:

1. A p-type material is deposited on the n-type material by diffusion process.
2. Both the materials are grown over silica glass.
3. For maximum light emission, an Aluminium anode is deposited at the outer edge of p-type material.
4. At the bottom of n-type material, a gold film is coated which acts as Cathode.



Working

1. When p-n junction is forward biased, the majority carriers from 'n' and 'p' regions crosses the junction and becomes minority carriers.
2. If the biasing voltage is further increased, the charge carriers recombines at the p-n junction by emitting light energy.
3. These electron-hole recombination rate determines the intensity (power) of light from the diode.

Advantages:

1. They are small, compact and low cost material.
2. They operates even at low voltage.
3. Response time is very fast (within 10^{-9} seconds)
4. They are operated at wide range of temperature.

Disadvantages:

1. Output power and intensity is low.
2. The light cannot travel long distance.

Applications:

1. They are used for optical communication system.
2. They are used in sensors, indicators, alarms and pilot light.

Organic Light Emitting Diode (OLED)

OLED is a solid state device which is made up of thin films of organic molecules that produce light with the application of electricity.

Principle:

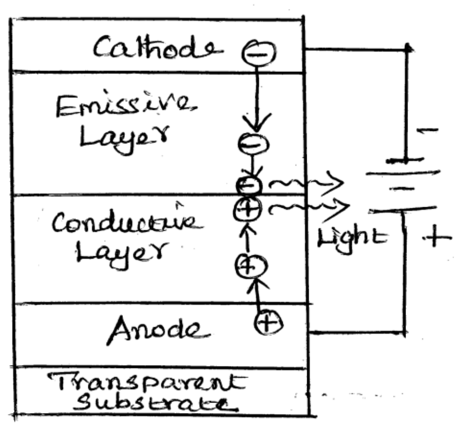
When an electric field is applied to OLED, the electrons moves from cathode to emissive layer and holes moves from anode to conductive layer. They recombine to produce photon.

Construction:

1. OLED consist of cathode and anode in between 2 organic layers called "Emissive layer" and "conductive layer".
2. All these layers are made up of organic polymer molecules grown over transparent substrate.
3. Anode is connected $+^{ve}$ terminal and cathode is connected to $-^{ve}$ terminal of the battery.

Working:

1.



1. When a voltage is applied across OLED, the cathode gives electrons to emissive layer and anode gives holes to the conductive layer.
2. Due to electrostatic force between electrons and holes, they recombine with each other.
3. The recombination of electrons and holes produces light energy.

Advantages:

1. Very thin and flexible.
2. Brighter than normal LED.
3. It does not require Backlighting.
4. It has large field of view.

Disadvantages:

1. Cost of manufacturing is very high.
2. Easily Breaks.
3. Blue OLED has less life time than Red OLED.

Applications:

1. They are used in cell phone, Digital camera ..etc.
2. They are used in computer Screen and TV monitor.
3. They are used in Real Time Video display.

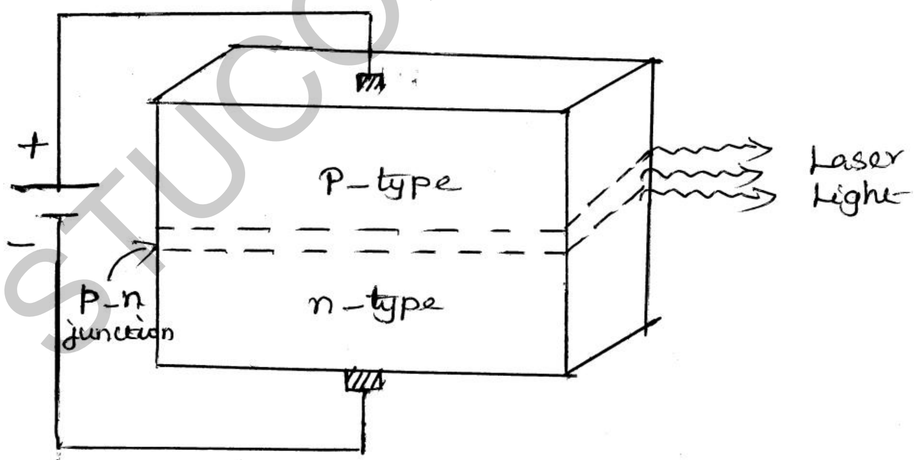
LASER Diode

It is a specially fabricated p-n junction diode. It emits laser light when it is forward biased.

Principle:

When the p-n junction is forward biased, the electrons from n-region and holes from p-region crosses the junction and recombine with each other. During the recombination, laser is emitted at the p-n junction.

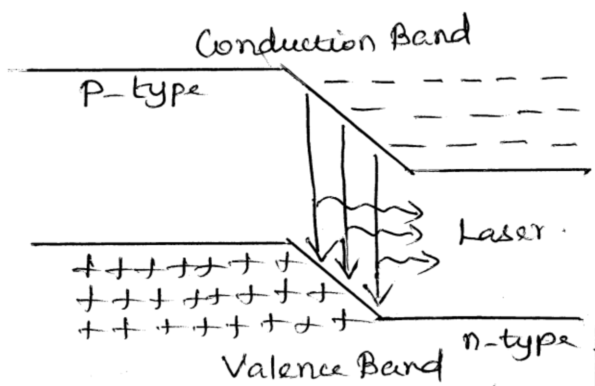
Construction:



1. The laser diode consist of 2 layers such as P-type Semi-conductor and n-type Semiconductor.
2. The metal electrodes are connected to upper surface of P-type material and lower surface of n-type material.
3. The surfaces are well polished.
4. The +ve terminal of the battery is connected to P-type material and -ve terminal of the battery is connected to n-type material.

Working:

1. When the p-n junction is forward biased, the electrons and holes are injected into p-n junction.
2. A large number of electrons and holes are accumulated at the C.B and V.B.
3. Due to increase in Voltage, these electrons move from V.B to C.B and recombines with each other.
4. During the recombination, Laser is emitted.
5. The polished surface of p-n material reflects the light internally until enough photons are generated.
6. When all photons have same frequency, they emitted at the p-n junction.



Advantages:

1. It is small in size and compact.
2. output can be easily increased by increasing input.
3. It emits continuous output.

Disadvantages:

1. Low output power
2. Poor monochromaticity and Stability.

Applications:

1. It is used in optical communication.
2. It is used in Bar code reader, Measuring device.
3. It is used as light source for Scanning images.

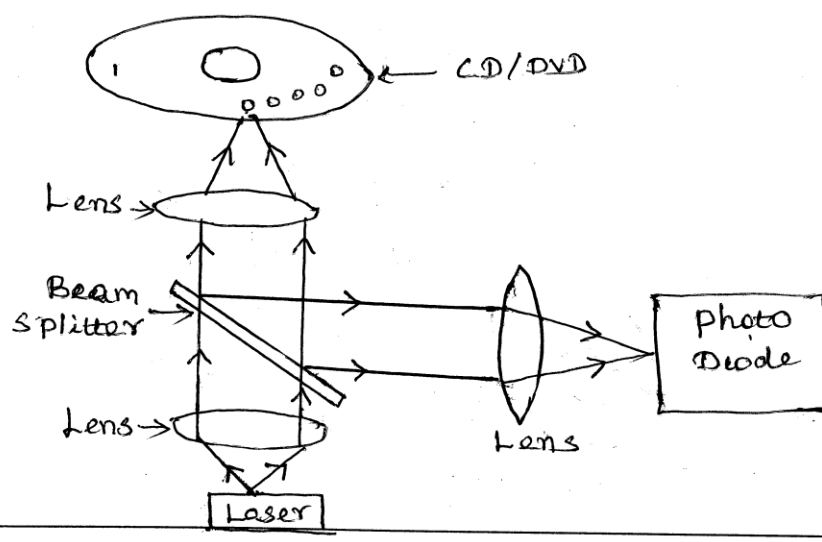
Optical Data Storage Techniques

An optical medium in which data is stored using laser is called as " Optical Data Storage Device".

There are various techniques used to store data using optical devices such as CD-ROM, CD-RW, DVD, Blue ray disk, magneto-optical disk and hologram.

Writing process in CD/DVD

1. Compact disk (CD) or Digital versatile disk (DVD) is a plastic (or) polycarbonate material.
2. It has a diameter of 120 mm and thickness 1.2 mm with a circular hole of 15 mm.
3. In the disk, data can be stored in tracks and sectors.
4. The optical arrangement of data storage on a disk is shown in the diagram.



5. As the CD rotates, the lens and beam follow the track under the control of motor.
6. The high power laser beam burns the surface of CD and creates a small hole called "Pit" which is referred as '1'. The remaining area will be referred as '0' called "Lands".

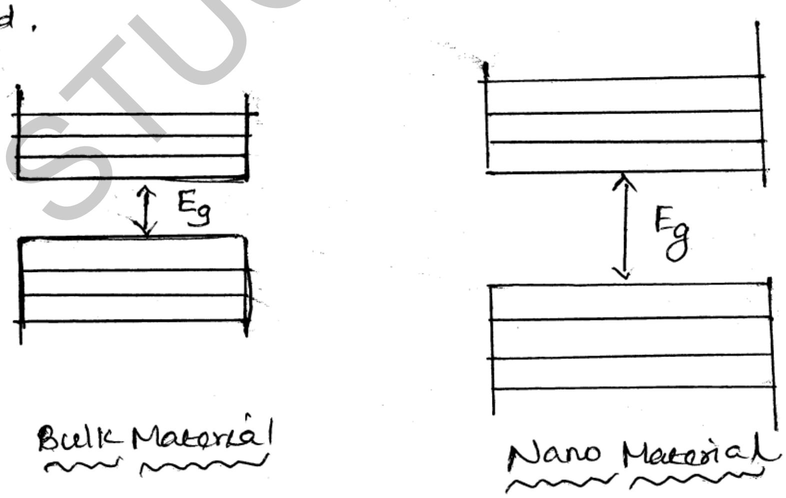
Reading Process

1. In this process, low power beam is used to read the data from the disk.
2. The laser is altered by the "Lands and Pits" along the recorded track through the lens and optical system to infrared photo diodes.
3. The signal from the photodiode is then used to reproduce the digitally recorded data.

Nano Devices / Nano Electronic Devices

Quantum confinement

1. The quantum confinement is defined as "the process of reducing the size of the solid so that the energy levels within the solid becomes discrete."
2. In this process, a small droplets of isolated electrons are created.
3. The movement of electrons are restricted in specific energy levels or in specific directions.
4. The electrical properties of quantum confined solid are altered.



5. If the size of the material is reduced to nanometer range, the energy levels become discrete and increases the Energy gap (E_g).
6. For quantum confinement, the volume of material is reduced to 1D, 2D, 3D along length, breadth, height of large solid.

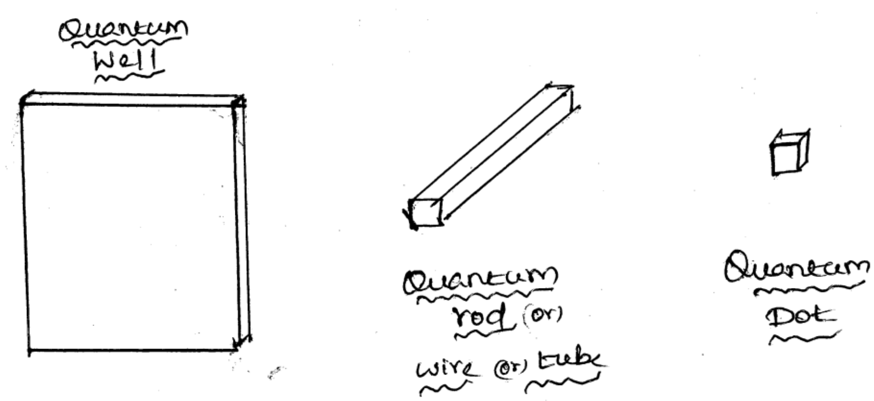
Quantum Structures

1. When the Bulk material is reduced in its size to the order of few nanometers, then the structure is called "Quantum Structures".
2. In a quantum confined structures, the movement of electrons are confined in one or more directions.
3. A quantum confined structure can be classified into 3 catagories such as
   (i) Quantum Well
   (ii) Quantum Wire
   (iii) Quantum Dot

(i) If one dimension is reduced to the nano range and other two dimensions are large, then the structure is called "Quantum well". (Ex) Semiconductor thin films.

(ii) If two dimensions are reduced to nano range and one dimension is large, then the structure is called "Quantum wire". (Ex) Nano wire, Nano rod, Nano tube.

(iii) If all three dimensions are reduced to nano range, then the structure is called "Quantum dot". (Ex) Atom.

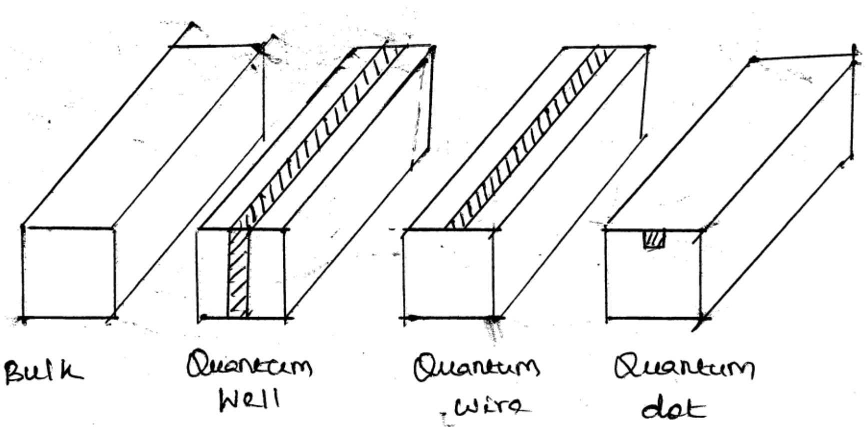


Structure	Quantum confinement	Number of Dimensions
Bulk	0	3 (x,y,z)
Quantum well	1 (z)	2 (x,y)
Quantum wire	2 (x,y)	1 (z)
Quantum Dot	3 (x,y,z)	0

4. A quantum well and quantum wires have atleast one dimension in which electrons are free to move. They are called "Partial Confinement".

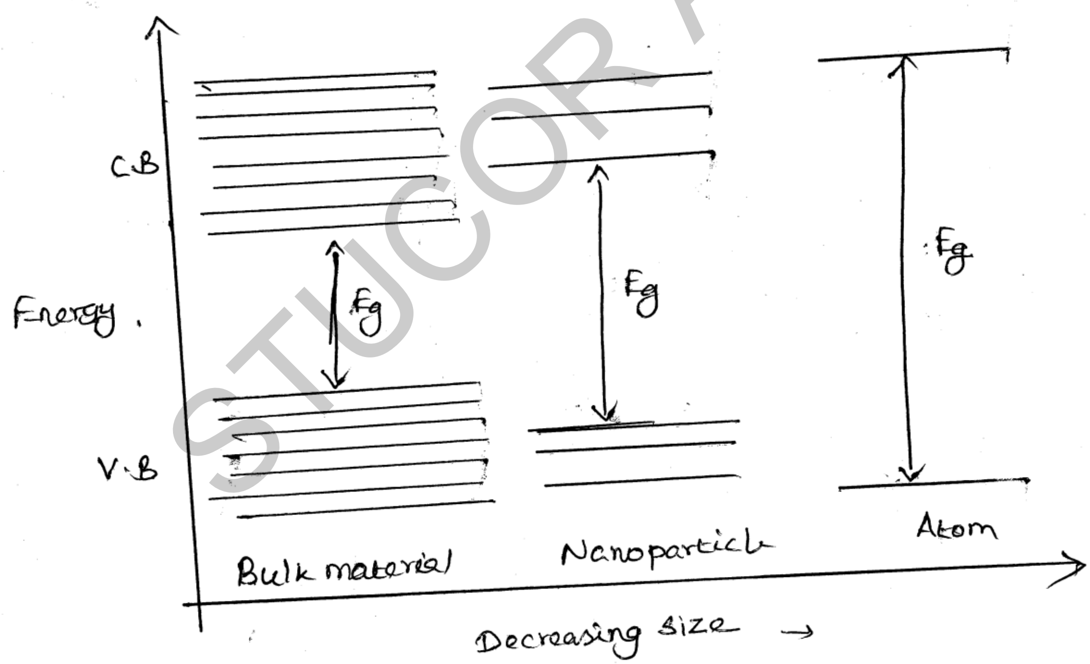
5. In quantum dot, the electrons cannot move in any direction, so it is called "Total confinement".

6. Quantum Structures in Bulk material is shown below



Band Gap of Nanomatereals

1. The electronic properties of metals and Semiconductors are determined by Band gap of the materials.
2. The band structure of the material changes with particle size.
   (ie) As the size of the material decreases, the energy level seperation increases.
3. This effect is responsible for the change of properties of metal or semiconductor.



4. The quantum size effect is very important for Semiconductor nanoparticles. Because, their bandgap increases with decrease in particle size.

5. For the nanomaterials, more external energy is required to excite the electrons from V.B to C.B. Because, the energy gap value is large.

6. So, when light photon falls on nanomaterials, only few electrons goes to C.B. They stay very short time and comes to V.B by releasing energy with different value.

7. (Eg): The Bulk Cadmium Sulfide is orange colour and its Band gap is 2.42 eV. If particle size is decreased, it becomes Yellow.

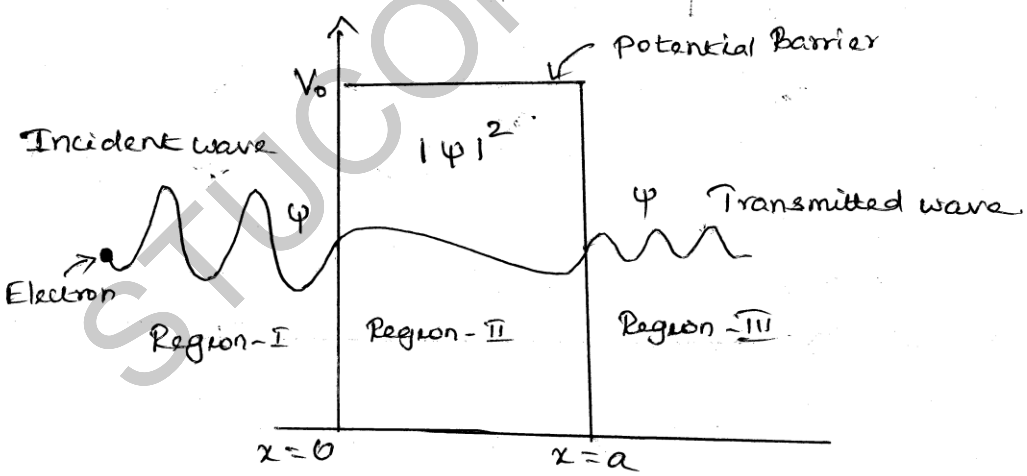
Tunneling

1. Tunneling is a "quantum process in which electron penetrates through the potential Barrier in an atomic structure".

2. Let us consider a particle of mass 'm' moving along x-axis.

3. The electron hits the potential barrier of thickness 'a', height 'V_0' (P.E) having energy "E".

4. If $E < V_0$, then the electron will be reflected back.
   If $E > V_0$, then the electron will be transmitted.



5. When the electron wave penetrates the barrier, it begins to decay and then again reappear on other side of the Barrier.

∴ This process is called "Electron Tunneling"

6. In region II, the probability density $|\psi|^2$ is non-zero function for the electron penetrating the Barrier which is called "Barrier penetration".

7. Thus, the tunneling is the result of wave properties of material particles.

8. The tunneling probability can be calculated by the transmission and reflection coefficients.

$$T + R = 1$$

Single Electron Phenomena

1. The ability to control the transfer of individual electron across quantum dot is called as "Single Electron phenomena".
2. For single electron phenomena to occur, a single electron should be isolated across the quantum dot.
3. An additional energy (E_c) is required for isolating electron in a quantum dot. This energy is called "Coulomb energy".

$$\text{Coulomb Energy } (E_c) = \frac{e^2}{2C}$$

where,

C = capacitance of quantum dot

e = charge of electron

4. This coulomb energy is verymuch greater than ($E_c >> kT$) thermal energy, which is used to control the electron in quantum dot.
5. The single electron phenomena is essentially based on "quantum tunneling" and coulomb Blockade.
6. The charging effect which stops or release the single electron into or from a quantum dot is called "Coulomb Blockade Effect".
7. This effect can be used as a ON-OFF switching device.
8. The condition for coulomb Blockade effect is expressed as

$$\text{Charging Effect } W_c = \frac{e^2}{2C} >> kT$$

9. If 2 or more charges near one another, they exert coulomb forces upon each other.

10. The phenomenon in which tunneling of single electron across the quantum dot is called as "Single electron tunneling".

11. So, the coulomb Blockade and Tunneling are the two process which are very important for single electron phenomena.

12. For example:

Transistor is very important component in electronic devices such as Amplifiers, Oscillators, Switches, Electro meters and Electronic circuits.

If these transistors are made as quantum dots, their properties are improved and its electron controling performance also increased.

Single Electron Transistor: (SET)

Definition:

A 3 terminal switching device which can transfer electrons from source to drain one by one is called as "Single Electron Transistor".

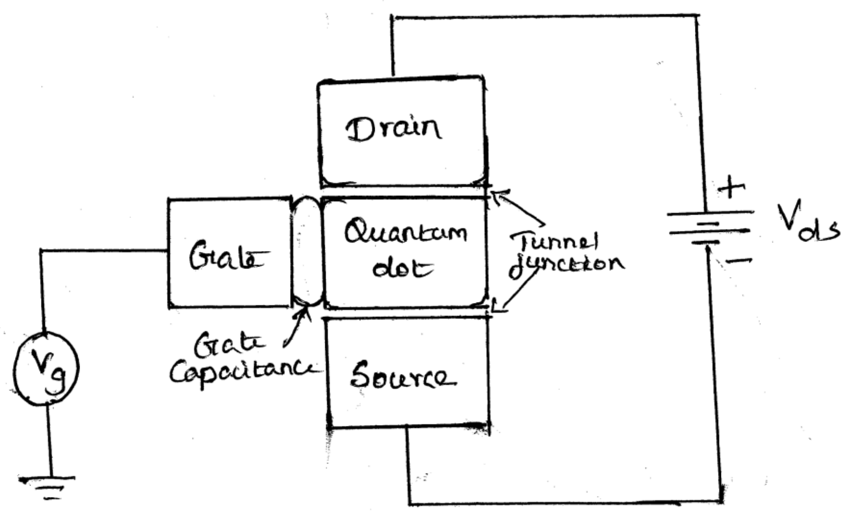
Principle:

A Coulomb Blockade effect and Resonant Tunneling Effect are the basic principles in SET

Construction:

1. SET has 3 terminals such as Source, Drain and Gate with 2 junction and quantum dot.

2. 2 Electrodes are connected to the source and drain to supply electrons and 1 electrode is connected to the gate to control the tunneling of electrons.



Single Electron Transistor

Working

1. At zero source-drain voltage (V_{sd}) and zero gate voltage (V_g), there is no flow of electrons from source to drain.

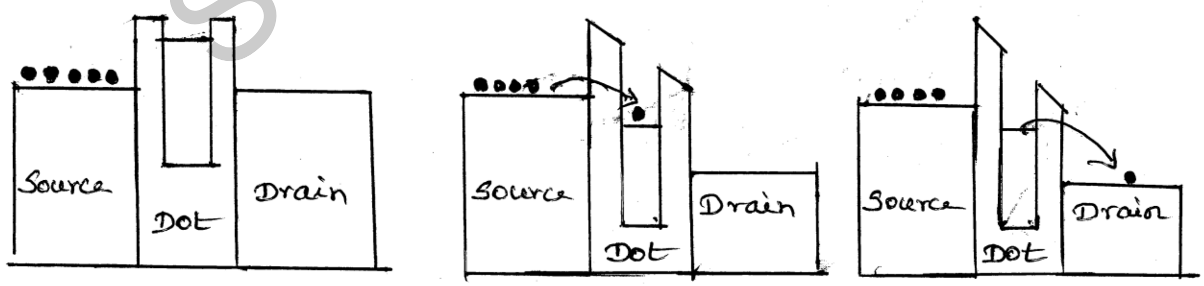
2. When the biasing voltage (V_{sd}) is applied across source and drain, then the electrons tunnel through dot in a uncontrollable manner.

3. Now the current flows from source to drain.

4. When a gate voltage (V_g) is applied to SET, it creates electric field and changes the potential energy of the dot w.r.t to source and drain.

5. This gate voltage controls the transfer of electron from source to dot and dot to drain.

6. For the current flow, the potential difference must be large to overcome the Coulomb Blockade energy.



$V_g = 0$ $\qquad$ $V_g = V_{Coulomb}$

7. The energy (E) required to the move the charge (Q) across the potential (V) is $\boxed{E = VQ}$

(or) $\boxed{V = \frac{E}{Q}}$ —— (1)

8. Since E = Coulomb Blockade energy $= \frac{e^2}{2C}$

Q = charge $= e$

∴ sub eqn (1)

Coulomb Voltage $V_{coulomb} = \frac{e^2/2C}{e}$

$$V_{coulomb} = \frac{e}{2C}$$

9. This is the voltage required to the dot so that the electron can Tunnel through it.

10. If Gate voltage $V_g = 0$, no current flows

If $V_g = V_{coulomb}$, Single electron Tunneling through dot at a time

If $V_g = V_{coulomb} + \frac{e}{2C}$, 2 electrons tunneling through dot at a time

If $V_g = V_{coulomb} + \frac{e}{2C} + \frac{e}{2C}$, 3 electrons tunneling through dot at a time.

11. Hence, the number of electrons in the quantum dot is controlled using gate voltage (V_g).

12. The gate voltage (V_g) for SET is few millivolts and source to drain voltage (V_{sd}) is pico ampere range.

Advantages:

- Fast Data transformation
- No wires required

Dis advantages:

- Size of quantum dot should be < 10 nanometer.
- Difficult to make.

Applications:

- Used for mass data Storage
- used in digital logic circuits
- used in Sensors and electrometers
- used for electron Spectroscopy
- used for next generation quantum computers.

Resonant Tunneling Diode

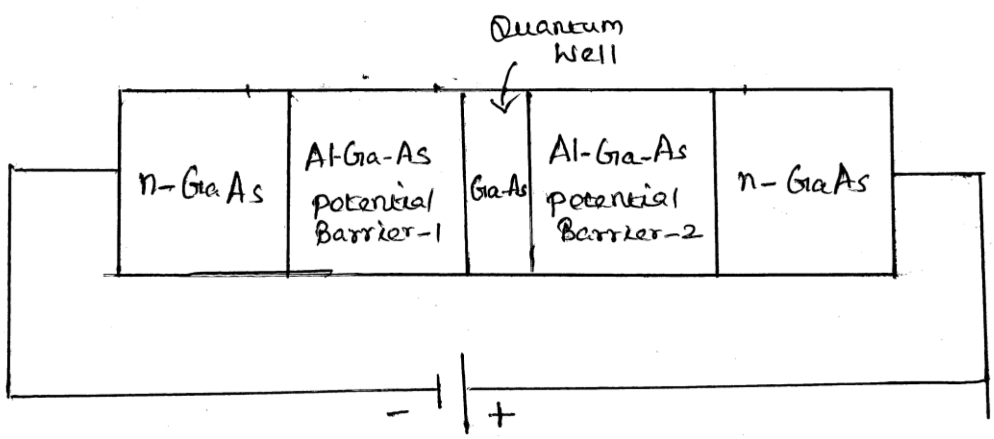
A diode that allows the electrons to tunnel through it at certain energy levels is called "Resonant Diode".

Principle

Resonant tunneling diode works on the principle of tunneling effect in which the electrons tunnel through the potential well, if energy of electron matches the energy level in the potential well.

Construction

1. The resonant tunneling diode consist of quantum well GaAs in between 2 potential barriers AlGaAs.
2. Both ends of the diode are made with heavily doped n type GaAs material so that the potential decreases drastically at the barriers.
3. This will help the electrons tunnel through the junction easily.
4. By applying a bias voltage, the tunneling current across the diode can be controlled.



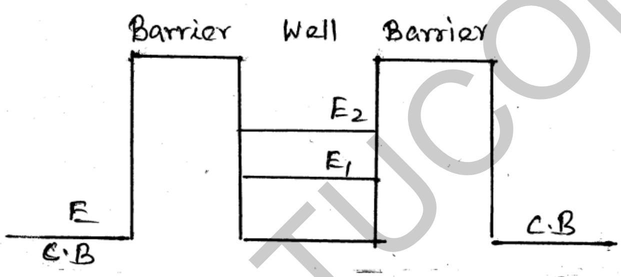
Working:

1. Without any biasing voltage, the electron energy level in the well is higher than the electron energy (E).

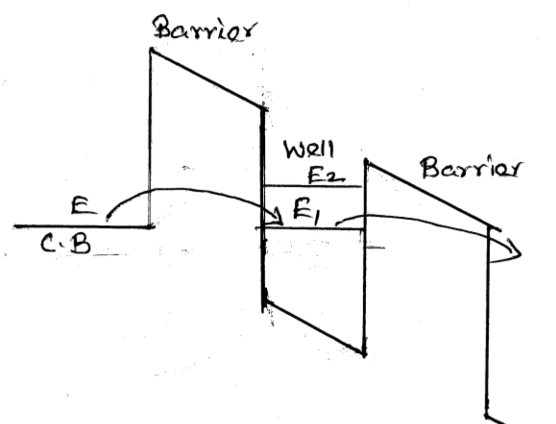
2. There is no current flow in diode and no electron can tunnel to the well.

3. If the biasing voltage is increased, the incident energy of electron becomes higher than the energy level in the potential well.

4. Now, the electrons can tunnel into the well causes tunneling current.



RTD Without Bias Voltage

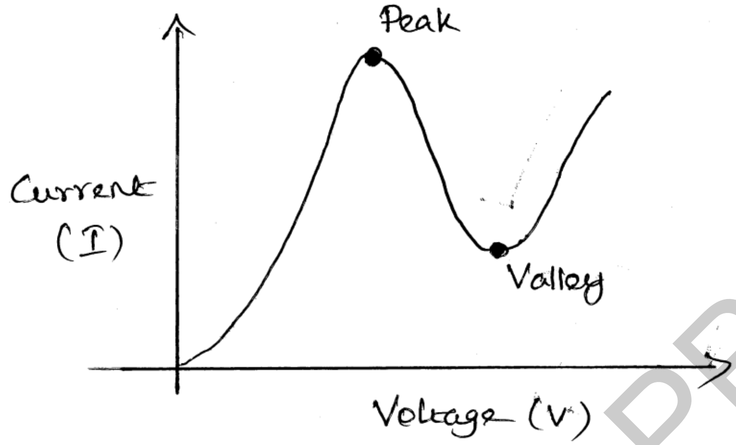


RTD With Bias Voltage

5. If the biasing voltage increases the tunneling of electrons through the diode also increases.

6. The V-I characteristics of tunnel diode can be studied as shown in the graph.

7. It represents, as the voltage increases, the tunneling current also increases and reaches a "peak" point.



8. When the Voltage is further increased, the energy of electron becomes less for barrier than the energy level in quantum well (E_2)

9. This results decrease in current which reaches a minimum Value point called "Valley".

10. The decrease in current with increase in Voltage is called as "Negative Resistance".

11. As the applied voltage continues to increase, the current begins to increase

Advantages

- Cost is low
- High speed of operation (Tera Hertz)
- Low power consumption
- It can be operated at room temperature.

Disadvantages

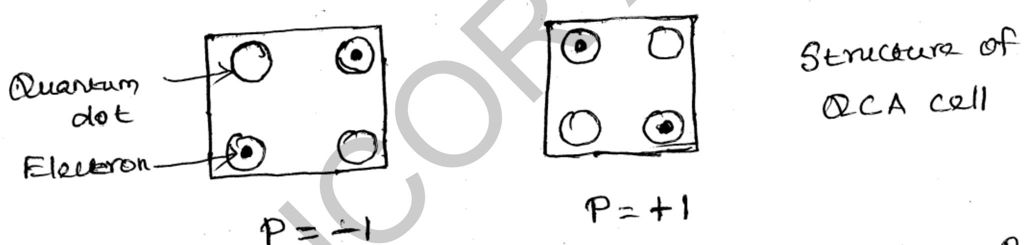
- Its a low output device
- Difficult to control i/p and o/p.

Applications

- It is used in Oscillators
- It is used in Integrated Circuits (IC's)
- It is used in switching devices (on/off).
- It is used in optical communication

Quantum Cellular Automata (QCA)

1. Quantum cellular Automata (QAC) is a "new nanotechnology which are used to build future computers".
2. Their circuit design are at the Nano-Scale range.
3. A quantum cellular automaton consist of "large array of cells (or) memory locations that are capable of storing numerical data".
4. The quantum cells consists of 4 quantum dots at the corners of the square shaped structure.



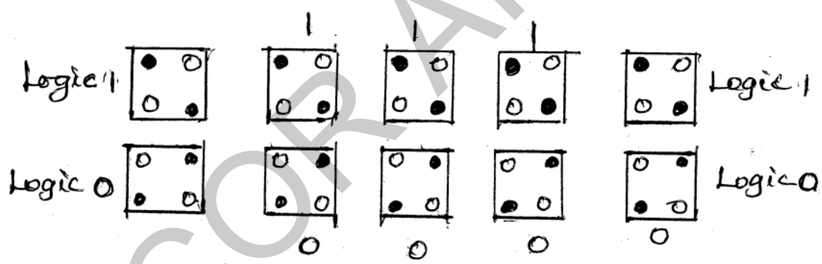
5. 2 electrons are allowed to move between the dots. But, they cannot come out from the cell because of high potential barrier.
6. Due to coulomb interactions, the electrons can be located at opposite ends of a diagonal and not at the same edge.
7. The logic operations in QCA is not expressed by high or low voltages. But, they are expressed by a binary number '1' and '0'.
8. In QCA, the potential barriers between adjacent quantum dots can be controlled by clocking scheme (External voltage).
9. But, the charge configuration one cell can alter the charge configuration of next cell.

10. If many cells are place together, they form a wire.

11. 2 electrons present in quantum dots along diagonal edge of the cell is termed as "polarization".

12. There are two stable polarization in the cell where the electrons have minimum energy.

P = +1 represents logic 1 &
P = -1 represent logic 0.



13. Logical AND and OR functions can be implemented from majority input with binary values 0 and 1. Also, a signal can be inverted by not gate.

14. QCA can be fabricated by (i) Semiconductor Technology
(ii) Molecular Technology
(iii) Magneto Nanoparticle Technology
(iv) Metal island Technology.

15. Advantages of QCA

- Small Area
- High Speed Switching
- Low power consumption

16. Applications of QCA

- Used in Satellites and Radars
- Used in Parallel computation
- Used in Image processing
- Used in Artificial Intelligence

Quantum System for information Processing (QIP)

1. "A quantum mechanics or system which performs computational tasks for information processing is called "Quantum Information Processing".

2. A system that uses more than one states of any quantum object to store, process and transmit data is known as "quantum system"

3. The simplest quantum system is quantum bit or qubit. If the quantum system exist in more than one state simultaneously, then it is called "Superposition".

4. A large scale quantum computer can be built using a "Controllable quantum system".

5. In classical computing, a bit has only one state either '0' or '1'. But in quantum computing, a bit has linear combination of both states '0' and '1'

6. The quantum state of a system is described by a complex function (ψ) which encodes all the information about the system.

Procedure for QIP

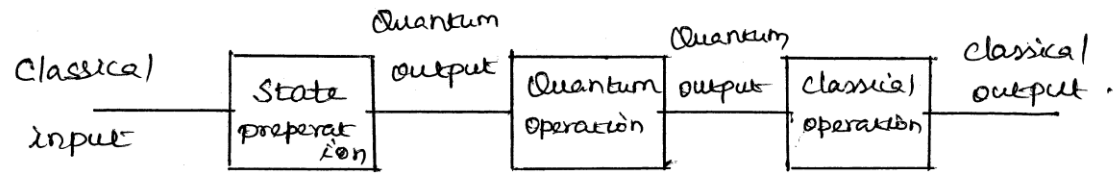
There are 3 steps involved in QIP

Step-1 The conversion of classical input to quantum output to initialize the state

Step-2 The quantum system performs quantum operations that evolve its state. Both i/p and o/p are in quantum state.

Step-3: The i/p is quantum and the o/p is classical. (ie) Readout some classical data from quantum system.

7. There 3 steps ~~of~~ QIP involves - storing, processing and computing the information based on quantum mechanics.



8. Applications of QIP

- Secure communication
- To solve many computational problems
- Development in crytography
- New methods for metrology
- Efficiently simulate physical systems.

Quantum States

1. The quantum state of a system (atom) is described by a complex function (ψ) which encodes all the information about the system.

2. The probability of finding the particles along x-axis in a quantum system is $\int \psi^* \psi \, dx = |\psi|^2 = 1$

3. So, In quantum mechanics, different notations are used to represent the "quantum states".

4. The quantum state of a system is denoted by a vector $|\psi\rangle$ and this quantum state is obtained by gathering all physical properties of quantum system like position, momentum, spin and polarization

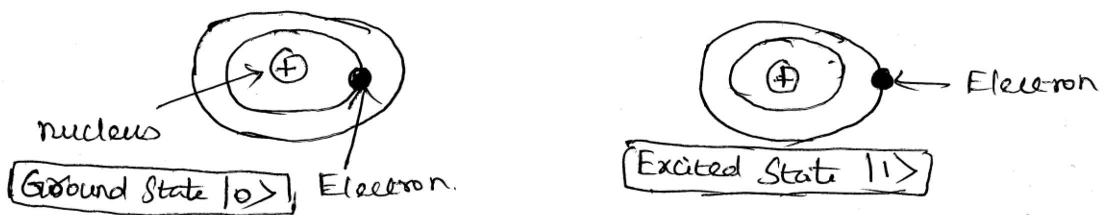
5. If two quantum states such as $|\psi\rangle$ and $|\chi\rangle$ combined together in a system as $\langle\psi|\chi\rangle$ then, they are said to be orthogonal.
6. The left part is called "bra" and the right part is called "ket".

Classical Bits

1. A classical bit is a digital representation of 2 states of a physical system.
2. Each bit is basically the "charge of an electron".
3. If the electron is charged, the bit is assumed to carry a value 1.
4. If the electron is not charged, the bit is assumed to carry a value 0.
5. So, A classical bit can be in state 0 (or) state 1.
6. A bit can store one piece of information. Large amount of information can be stored in a sequence of bits.
7. The bits are building blocks of all modern computers. They do computation like storing information, retrieving the information and changing the state of physical system.

Quantum bits (or) Qubits

1. The basic unit of physical information in the state of quantum system is called "Quatum bit or Qubit".
2. A qubit uses the quantum mechanical concept of superposition to achieve a linear combination of 2 states, of '0' or '1'.
3. It is the fundamental unit of computation in quantum computers.
4. The superposition of 2 states at any time can be expressed in percentage. (Eg) 30% 1 & 70% 0 (or) 40% 1 & 60% 0 or any other combination.
5. The physical information are (i) polarized photons
   (ii) Electron spin up or down
   (iii) Defined energy levels of atom or ion
   (iv) Superconducting circuits.
6. Let us consider an electron in a hydrogen atom in the ground state or in the excited state.



7. In classical system, the ground state represent |0> and the excited state represents |1>
8. But in quantum system, the electron will exists in a linear combination ground state and Exited state.

9. The electron will exists in the ground state $|0\rangle$ with probability amplitude α and in the excited state $|1\rangle$ with probability amplitude β.

(ie) $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

Where, α, β = probability amplitudes which are complex values.

(ie) $|\alpha|^2 + |\beta|^2 = 1$

10. The probability of superposition states $|0\rangle$ and $|1\rangle$ are represented as $|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$

$|1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$

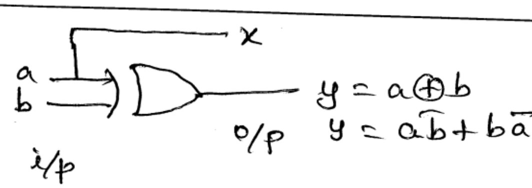
$\therefore |\psi\rangle = \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$

11. The probability amplitudes α and β encode more data in the quantum system.

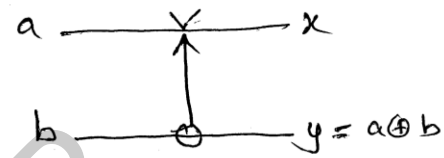
CNOT gate

1. Controlled NOT gate is known as CNOT gate,
2. It is a simple 2 qubit gate which performs exclusively OR operation on 2 input qubits and write the output to second qubit.
3. The first i/p is referred as "data i/p" and other as "control". Both i/p are feed with either 0 or 1.
4. The general representation of CNOT gate is followed as

(i) The symbol of CNOT gate is



(ii) The graph of CNOT gate is



(ii) If $a = 0$, y = target of b
If $a = 1$, y = inverse of target b

(iii) The truth table of CNOT gate is

Input		Output	
Control input	Target Qubit	Control Qubit	Target output
a	b	x	$y = a \oplus b = a\bar{b} + b\bar{a}$
0	0	0	0
0	1	0	1
1	0	1	1
1	1	1	0

(iv) The matrix of CNOT gate is

$$CNOT = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

5. Properties of CNOT gate

(i) They require only 2 inputs
(ii) They dissipate less heat
(iii) They are reversible gate

6. Applications

(i) Designing quantum computers
(ii) Quantum Error correction
(iii) Quantum Teleportation

Note:

Bra Vectors — Ket Vectors

1. $0 = |0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ & $\langle 0| = (1\ 0)$

$1 = |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$ & $\langle 1| = (0\ 1)$

2. For Bra Vectors

$00 = |00\rangle = |0\rangle \otimes |0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \otimes \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$

$01 = |01\rangle = |0\rangle \otimes |1\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \otimes \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}$

$10 = |10\rangle = |1\rangle \otimes |0\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \otimes \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}$

$11 = |11\rangle = |1\rangle \otimes |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \otimes \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$

IIIly. For Ket Vectors

$\langle 00| = (1\ 0\ 0\ 0)$

$\langle 01| = (0\ 1\ 0\ 0)$

$\langle 10| = (0\ 0\ 1\ 0)$

$\langle 11| = (0\ 0\ 0\ 1)$

3. $|00\rangle\langle 00| = \begin{bmatrix}1\\0\\0\\0\end{bmatrix}(1000) = \begin{bmatrix}1&0&0&0\\0&0&0&0\\0&0&0&0\\0&0&0&0\end{bmatrix}$

$|01\rangle\langle 01| = \begin{bmatrix}0\\1\\0\\0\end{bmatrix}(0100) = \begin{bmatrix}0&0&0&0\\0&1&0&0\\0&0&0&0\\0&0&0&0\end{bmatrix}$

$|10\rangle\langle 11| = \begin{bmatrix}0\\0\\1\\0\end{bmatrix}(0001) = \begin{bmatrix}0&0&0&0\\0&0&0&0\\0&0&0&1\\0&0&0&0\end{bmatrix}$

$|11\rangle\langle 10| = \begin{bmatrix}0\\0\\0\\1\end{bmatrix}(0010) = \begin{bmatrix}0&0&0&0\\0&0&0&0\\0&0&0&0\\0&0&1&0\end{bmatrix}$

Multiple Qubits

1. Definition:

A combination of many qubits and quantum state which carry many complex amplitudes are called "Multiple Qubits".

2. Let us consider a single bit has 2 states & similarly 2 bits will have four possible states. Such as.

(ie) Qubit: 00 01 10 11

States: 1 2 3 4

3. The quantum states for 2 bits are

$$|\psi_1\rangle = \alpha_0|0\rangle + \alpha_1|1\rangle$$

$$|\psi_2\rangle = \beta_0|0\rangle + \beta_1|1\rangle$$

Where, α, β = probability amplitudes (or) complex coefficients

4. The combination of 2 quantum states can be written as

$$|\psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle$$
$$= (\alpha_0|0\rangle + \alpha_1|1\rangle) \otimes (\beta_0|0\rangle + \beta_1|1\rangle)$$

$$\therefore |\psi\rangle = \alpha_0\beta_0|0\rangle|0\rangle + \alpha_0\beta_1|0\rangle|1\rangle + \alpha_1\beta_0|1\rangle|0\rangle + \alpha_1\beta_1|1\rangle|1\rangle$$

(or) $$|\psi\rangle = |0\rangle \otimes |0\rangle + |0\rangle \otimes |1\rangle + |1\rangle \otimes |0\rangle + |1\rangle \otimes |1\rangle$$

5. These 2 qubit states can be represented as single state as,

$$\alpha_0\beta_0 = C_0,\ \alpha_0\beta_1 = C_1,\ \alpha_1\beta_0 = C_2,\ \alpha_1\beta_1 = C_3$$

$$\therefore |\psi\rangle = C_0|00\rangle + C_1|01\rangle + C_2|10\rangle + C_3|11\rangle$$

Where, $|C_0|^2 + |C_1|^2 + |C_2|^2 + |C_3|^2 = 1$

6. Hence, a collection of 'n' qubits will have 2^n states which are used for quantum computing.

7. So far 7 qubit quantum computer has been built.

Bloch Sphere

1. Bloch sphere is "a geometric representation of qubit states in terms of points on the surface of a unit sphere".

2. Many operations on a single qubit are commonly used in quantum information processing with bloch sphere structure.

3. Let us consider a bloch sphere represented by a complex number ψ.

(i) $\psi = x + iy$ {where x, y = Real numbers

$x = \cos\frac{\theta}{2}$ & $y = \sin\frac{\theta}{2}$

$i = e^{i\phi}$ with

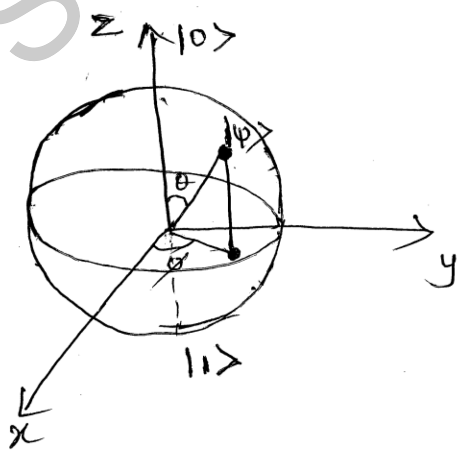
$0 \leq \theta \leq \pi$ and $0 \leq \phi \leq 2\pi$}

$\therefore \psi^* = x - iy$

$\therefore |\psi|^2 = \psi \psi^*$

$= (x+iy)(x-iy)$

$|\psi|^2 = x^2 + y^2 = 1$ which is the equation of circle of radius



4. The north pole and south pole of the bloch sphere are defined as the basis states $|0\rangle$ and $|1\rangle$ corresponding to the surface of the sphere in 3 axis.

5. A qubit can be any point on the sphere. The complex state of qubit $|\psi\rangle$ makes an angle 'θ' with Z-axis and makes an angle 'ϕ' with the x-y plane and the projection of qubit.

6. The linear combination of 2 states (superposition) happens because of wave nature of electron particles.

7. But, if the qubit is closer to either or north pole, there is a collapse of quantum state $|\psi\rangle$

8. If the qubit is exactly at the equator, there 50-50 chance to collaps to any one the poles.

9. Hence, we can conclude that, it is possible to store large amount of information on a single qubit but it is impossible to retrieve the information.

10. When the value is measured, the qubit returns $|0\rangle$ with probability α^2 or it returns $|1\rangle$ with probability β^2, then the qubit is assumed to be the state just returned.

Quantum Gates

1. Quantum gate is a "Basic quantum circuit operating with a small number of qubits".
2. These gates are used to transform the qubits to manipulate quantum information signal and form quantum computing system.
3. Quantum gates are reversible and will not lose input signal.
4. Quantum gates do not have heat dissipation problems.
5. According to the number of input qubits, quantum gates are classified as

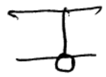
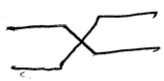
   Unary gates - Gates that take one qubit as input

   Binary gates - Gates that take two qubit as input

   Multi qubit gates - Gates that take multiple qubit as input

6. Some of the quantum logic gates in a matrix form can be written as follows,

Operator	Quantum Logic Gate	Number of Qubit	Matrix
pauli - x	—[X]—	1 qubit	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
pauli - y	—[Y]—	1 qubit	$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
pauli - z	—[Z]—	1 qubit	$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Hadamard	—[H]—	1 qubit	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$

phase shift Gate	—[S]—	1 qubit	$\begin{bmatrix} 1 & 0 \\ 0 & -i \end{bmatrix}$
$\frac{\pi}{8}$ gate	—[T]—	1 qubit	$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$
CNOT gate		2 qubit	$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$
SWAP gate		2 qubit	$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

#. These basic quantum gates combine to form complex logic gates which develops the entire Quantum Information system".

Advantages of Quantum Computing over classical computing

1. The quantum computers can solve the complex mathematical problems which is impossible in classical computers.
2. A quantum computer is 1000 times faster than any classical computer.
3. A quantum computer consumes less energy to process large amount of data (2.5 Exabyte = 5 million laptops) comparing to classical computer.
4. A quantum computer handles big problems in simple steps which is very difficult in classical computer.

5. In quantum computing 0's and 1's both can be represented simultaneously. But in classical computing, either 0 or 1 is represented. Both cannot be represented at the same time.

6. The simulation efficiency is high in quantum computers than in classical computers.

6. Quantum computing is suitable for secure communication with high level accuracy than classical computing.

7. Quantum computing is done using qubits. But classical computing is done using bits.

Applications of quantum computing

1. It is used in Machine Learning and Artificial Intelligence
2. It is used for drug design and development.
3. It is used in cyber security and cryptography.
4. It is used in weather forcasting.
5. It is used for science research.