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1(a). Electrical Properties of materials

Part - A

1. Define Electrical Conductivity?

The amount of electric charge (Q) conducted per unit time (t) across unit area (A) of the solid per unit applied electrical field (E).

$$\sigma = \frac{q}{tAE}$$

2. What are the merits of classical free electron theory?

(i) It is used to verify Ohm's law

(ii) It is used to explain electrical and thermal conductivities of metals

(iii) It is used to derive Wiedemann – Franz law

(iv) It is used to explain the optical properties of metal.

3. What are the drawbacks of the classical free electron theory?

(i) Classical theory states that all free electrons will absorb the supplied energy. But quantum theory will absorb certain amount of supplied energy

(ii) Electrical conductivity of semiconductors and insulators could not be explained by this theory

(iii) The phenomenon such as photo – electric effect, Compton effect and black body radiation could not be explained by this theory

4. Define Mean free path?

The average distance travelled by a free electron between any two successive collisions in the presence of an applied field is known as mean free path

$$\lambda = v_d \times \tau_c$$

5. Define collision time?

The average time taken by a free electron between two successive collisions of the electrons is known as collision time

6. Define relaxation time of an electron?

The average time taken by a free electron to reach its equilibrium position from the distributed position due to application of an external electric field is called relaxation time.

7. Define Drift velocity?

The velocity acquired by the free electron due to the application of electric field in the direction opposite to the direction of electric field.

8. Define mobility of electrons?

The magnitude of the drift velocity per unit electric field is defined as the mobility of the electrons $\mu = \frac{v_d}{E}$

unit: $mV^{-1} S^{-1}$

9. State Wiedemann – Franz law? Give the Lorentz number and its value?

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"The ratio of electrical conductivity (K) to the thermal conductivity (σ) is directly proportional to absolute temperature (T). i.e., $\frac{K}{\sigma} \infty T$ (or) $\frac{K}{\sigma} = LT$

Where L is the Lorentz number and experimentally, $L = 2.44 \times 10^{-8}\ W\Omega K^{-2}$ at T = 273K

10. What are the sources of the resistance in the metals?

(i) Impurities (ii) Temperature (iii) Number of free electrons

11. Define Fermi energy and Fermi level with its importance?

Fermi Level is the state at which the probability of electron occupation is 50% at any temperature above 0K and also it is the highest reference energy level of a particle at absolute 0K.

Fermi energy is the energy of the state at which the probability of the electron occupation is 50% at any temperature above 0K. It is also the maximum energy of the filled states at 0K.

Importance: Fermi level and Fermi energy determine the probability of an electron occupying a given energy level at given temperature.

12. Define Fermi Distribution Function?

The probability of the electron F (E) occupying at a given energy level at temperature T is known as Fermi Distribution Function. It is given by

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

Where E_f – Fermi Level; k – Boltzmann Constant; T – Temperature

13. Define density of states. What is its use?

It is defined as the number of available electron states per unit volume in an energy interval E and E+dE. It is denoted by Z(E)

i.e., $Z(E) = \frac{\text{No. of available energy states between E and E+dE in a cubical metal piece}}{\text{Volume of that cubical metal piece}}$

14. What are bound and free electrons?

The electrons which are attached to the atoms and bound to the atomic lattice are called bound electrons. The valence electrons of an atoms free to move throughout the volume of metal like gas molecules of a container are called free electrons.

15. What are the salient features of quantum theory of free electrons?

According to sommerfield quantum theory, free electrons obey quantum law. They cannot have all possible energies but have quantized energy values. Also their distribution in different possible energy levels obeys Fermi – Dirac distribution law.

16. Arrive the microscopic form of Ohm's law? Whether it is true for all temperature?

According to macroscopic theory, Ohm's law is V = IR

We know that resistivity is given by $\rho = \frac{RA}{l}$ where R – resistance; A – area of cross section and l is the length of the specimen

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$\therefore V = I\,\frac{\rho l}{A}$

(or) $\frac{V}{l} = J\rho$

(or) **J = σE** $[\because E = \frac{V}{l}\,; J = \frac{I}{A}\ \&\ \rho = \frac{1}{\sigma}]$

This is the microscopic form of ohms law and it is not true for all the temperatures.

17. How does electrical resistivity of the metal varies with temperature?

When the temperature is increased, due to increase in thermal vibrations of atoms, the electrons make frequent collisions resulting in reduction of mean free path (λ) and hence resistivity increases.

Part – B

1. What are the assumptions of classical free electron theory? On the basis of free electron theory, derive an expression for electrical conductivity and thermal conductivity of the metal and hence obtain Wiedemann – Franz law? What are the shortfall and outcomes?

Assumptions

(1) All the metals are composed of atoms. Each atom has central nucleus surrounded by number of electrons in the permissible orbits

(2) The electrons in the metal are free to move in all possible directions about the whole volume of metal like molecules of a perfect gas in a container.

Absence of Electric field

(3) All the electrons are move in random direction and collide with each other elastically without any loss of energy

(4) The force between the conduction electron and ion core is neglected and the total energy of the electron is assumed to be Kinetic energy (Potential energy is zero)

Presence of electric field

(5) The free electrons moves in a direction opposite to the direction of the applied field(drifted towards positive potential)

(6) Since free electrons are assumed to be a perfect gas, they obey classical kinetic theory of gases and the free electron velocities in the metal obey Maxwell – Boltzmann statistics.

Electrical conductivity

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When an electric field (E) is applied between the extreme ends of a metallic rod, the electrons will move in opposite direction to the direction of applied field with a drift velocity V_d.

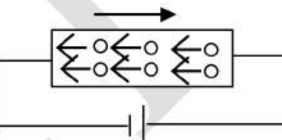
If ‘E’ is the electric field applied on an electron of charge ‘*e*’, then

Lorentz Force acting on the electron, F = eE (1)

This force accelerates the electrons and this accelerated electron collide with positive ion core and other free electrons elastically. After collision the electros losses its kinetic energy and velocity. Due to the driving force the electron will accelerated once again before its involve next collision.

Here, Acceleration (a) = $\frac{V_d}{\tau}$ (2)

Where V_d – drift velocity; τ – Relaxation Time



From Newton II law of motion, Force on the electron, F = mass (m) x acceleration (a) (3)

Sub. (1) in (3), we get $F = \frac{mV_d}{\tau}$ (4)

From equations (2) & (4) $eE = \frac{mV_d}{\tau}$ (or) $V_d = \left(\frac{e\tau}{m}\right)E$ (5)

From ohm’s law, the current density (J) is expressed in terms of electrical conductivity (σ) as

J = σ E (6)

Also, the current density in terms of drift velocity can be written as J = n e V_d (7)

Sub. (5) in (7), we get $J = ne\left(\frac{e\tau}{m}\right)E$ (or) $J = \frac{ne^2\tau}{m}E$ (8)

By comparing (6) and (8)

Electrical conductivity $\boxed{\sigma = \frac{ne^2\tau}{m}}$ (9)

Thus, the amount of electrical charges (Q) conducted per unit time (t) per unit area (A) of a solid along unit applied electrical field (E).is called electrical conductivity

$$\boxed{\sigma = \frac{q}{tAE}}$$

Thermal Conductivity

“It is defined as the amount of heat (Q) flowing per unit time through the material having unit area of cross section and maintaining at unit temperature gradient (dT/dx)”

Consider A = 1m^2 & t = 1 sec,

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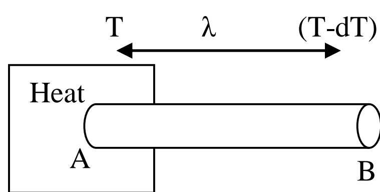
i.e., $Q = K\frac{dT}{dx}$ (or) $K = \frac{Q}{\frac{dT}{dx}}$ (10)



Consider two cross sections 'A' at high temperature (T) & 'B' at low temperature (T-dT) in a uniform metallic rod 'AB'. Two cross sections 'A' and 'B' are separated by a distance 'λ'. The conduction of heat takes place from 'A' to 'B' through electrons. During collision, electrons near 'A' lose their kinetic energy while electrons near 'B' gains the energy

Let the density of conduction electron be 'n' and velocity of electron be 'v'.

At 'A' average kinetic energy of the electron = $\frac{3}{2}kT$ $\quad \because K.E = \left[\frac{1}{2}mv^2 = \frac{3}{2}kT\right]$ (11)

Where k – Boltzmann Constant and T – absolute temperature

At 'B' average kinetic energy of the electron = $\frac{3}{2}k(T-dT)$ (12)

∴ Excess Kinetic energy from A to B of an electron = $\frac{3}{2}kT$ - $\frac{3}{2}k(T-dT)$ = $\frac{3}{2}kdT$ (13)

Number of electrons crossing unit area per unit time from 'A' to 'B' = $\frac{1}{6}nv$ (14)

Excess energy carried from 'A 'to 'B 'for unit area in unit time = $\frac{1}{6}nv$ x $\frac{3}{2}kdT$ = $\frac{1}{4}nvkdT$ (15)

III^{rly}, Deficient energy carried from 'B' to' A' for unit area in unit time = -$\frac{1}{4}nvkdT$ (16)

Net amount energy transferred from 'A 'to 'B' $Q = \frac{1}{4}nvkdT - (-\frac{1}{4}nvkdT)$

(or) $Q = \frac{1}{2}nvkdT$ (17)

But, by definition $Q = K\frac{dT}{dx}$ (or) $Q = K\frac{dT}{\lambda}$

$\therefore K = \frac{1}{2}nvk\lambda$ (18)

W.K.T for metals, relaxation time (τ) = Collision time (τ_c).

i.e., $\tau = \tau_c = \frac{\lambda}{v}$ (or) $\tau v = \lambda$ (19)

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Sub. Eqn (19) in (18), we get $\therefore K = \frac{1}{2} n v^2 k \tau$ (20)

This is the Expression for Thermal Conductivity

Wiedemann – Franz Law

Dividing equation (20) by (9), we get, $\frac{Thermal Conductivity}{Electrical Conductivity} = \frac{K}{\sigma} = \frac{\frac{1}{2} n v^2 k \tau}{\frac{ne^2 \tau}{m}}$

$$\text{(or)} \quad \frac{K}{\sigma} = \frac{1}{2} \frac{mv^2 k}{e^2} \qquad (21)$$

W.K.T the kinetic energy of an electron is $\frac{1}{2} mv^2 = \frac{3}{2} kT$

Then, equation (21) becomes $\frac{K}{\sigma} = \frac{3}{2} \times \frac{kT \times k}{e^2} = \frac{3}{2} \left(\frac{k^2}{e^2} \right) T$

$$\text{(or)} \quad \boxed{\frac{K}{\sigma} = LT}$$

Where L = $\frac{3}{2} \left(\frac{k^2}{e^2} \right)$ is a constant called Lorentz number. By substituting the value of

k = 1.38 x 10^{-23} JK^{-1}, e = 1.6 x 10^{-19} Coloumb, L = 1.12 x 10^{-8} $W\Omega K^{-2}$.

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

Thus "The ratio of Thermal Conductivity to Electrical Conductivity of a metal is directly proportional to absolute temperature of the metal"

Success of classical free electron theory

i. It is used to verify Ohm's law
ii. It is used to explain electrical and thermal conductivities of metals
iii. It is used to derive Wiedemann – Franz law

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iv. It is used to explain the optical properties of metal

Failure of classical free electron theory

i. Classical theory states that all free electrons will absorb the supplied energy. But quantum theory will absorb certain amount of supplied energy
ii. Electrical conductivity of semiconductors and insulators could not be explained by this theory
iii. The phenomenon such as photo – electric effect, Compton effect and black body radiation could not be explained by this theory
iv. The theoretical and experimental values of electronic specific heat and specific heat are not matched
v. The ratio of thermal to electrical conductivity is not constant at all temperature
vi. The experimental and theoretical values of Lorentz number are not matched.

2. Write the Fermi - Dirac distribution function. Explain how Fermi - function varies with temperature?

'The Probability F (E) of an electron occupying a given energy level at absolute temperature is called Fermi - Dirac distribution function

i.e., $F(E) = \frac{1}{1+e^{\frac{(E-E_f)}{kT}}}$ where E – energy of the level whose electron occupancy is being considered; E_f – Fermi energy; k – Boltzmann constant; T – absolute temperature

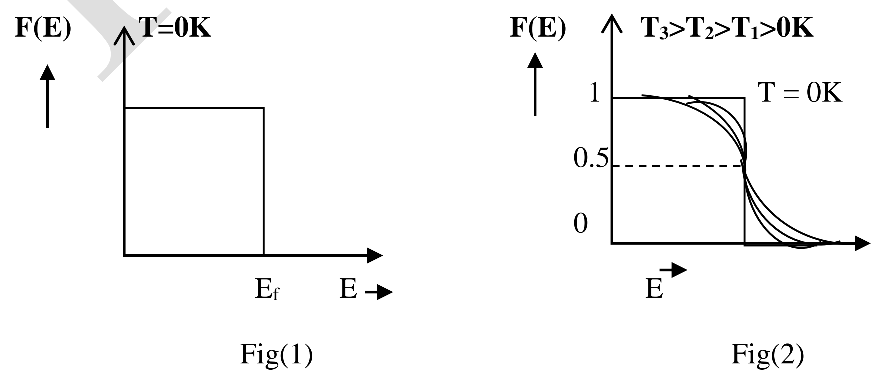
Effect of temperature on Fermi function

Case 1: at T = 0 K for E < E_f , $F(E) = \frac{1}{1+e^{\frac{(Some-VeValue)}{0}}} = \frac{1}{1+e^{-\alpha}} = \frac{1}{1} = 1$

∴ F(E) = 1Thus, there is a 100% chance of electron occupy below the Fermi energy of the energy level

Case 2: at T = 0 K for E > E_f , $F(E) = \frac{1}{1+e^{\frac{(Some+VeValue)}{0}}} = \frac{1}{1+e^{\alpha}} = \frac{1}{1+\alpha} = \frac{1}{\alpha} = 0$

∴ F(E) = 0 Thus, there is a no chance of electron occupy above the Fermi energy of the energy level



Fig(1) Fig(2)

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Case 3: At any temperature other than 0K and E= E_f , $F(E) = \frac{1}{1+e^0} = \frac{1}{1+1} = \frac{1}{2} = 0.5$

There is a 50% chance for the electron to occupy Fermi energy level

With increase in Temperature, i.e., T>0K, Fermi function F (E) varies with 'E' as shown in figure (2)

At very high temperature when (thermal energy) kT >>E_f (or) T → α, electron lose their quantum mechanical behavior and the Fermi distribution function reduces to classical Boltzmann distribution.

Uses:

(i) It gives the probability of the electron occupation at the given energy state at given temperature

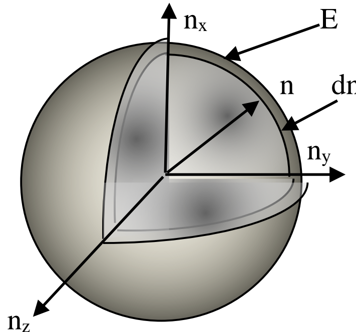
(ii) It is used to calculate the number of free electrons per unit volume at given temperature

(iii) It is used to calculate the Fermi energy of the metal

3. (i) Obtain an expression for the density of states for the metal.
   (ii) How it is used to calculate the Fermi energy of the metals? Give its importance.
   (iii) What happen for non-zero temperature?
   (iv) Discuss the average energy of electrons at zero Kelvin.

Density of States:

It is defined as the number of available electron states per unit volume in an energy interval E and E+dE. It is denoted by Z(E)



$$Z(E) = \frac{Number\ of\ available\ energy\ states\ between\ E\ \&\ E + dE\ in\ a\ metal\ piece\ (N(E)\ dE)}{Volume\ of\ the\ metal\ piece\ (a^3)}$$

Let us consider a cubical metal piece of side 'a'. The electron will behave as a wave in this metal and confined with the allowed energy levels.

The energy of the electron in three dimensional potential well is $E = \frac{h^2}{8ma^2}\ (n_x^2 + n_y^2 + n_z^2)$ (1)

where the energy of an electron is determined by sum of the square of quantum numbers (n_x, n_y, n_z). For this, A imaginary sphere is constructed with quantum numbers n_x, n_y, n_z as three coordinate axes in a three dimensional

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space. A radius vector 'n' is drawn from the origin 'O' to a point n_x, n_y, n_z. it is observe that, all the points lie on the surface of this sphere will have same energy 'E'.

Thus, $n^2 = n_x^2 + n_y^2 + n_z^2$ denotes the radius of the sphere with energy 'E'. This sphere is further divided into many shells. Each shell represents a particular combination of quantum numbers and therefore represents particular energy value

Let us consider two such energy values E and E+dE. The number of available energy states between E and E+dE can be determined by finding the number of energy states between the shells of radius n and n+dn.

Number of energy states within a sphere of radius 'n' = $\frac{4}{3}\pi n^3$ **(1)**

Since the quantum number n_x, n_y, n_z have only +ve integer value, we have to take only one octant of sphere $\left(\frac{1}{8}\right)$

∴ No. of available energy states within one octant of sphere of radius 'n' Corresponding to energy 'E' $= \frac{1}{8} \times \left[\frac{4}{3}\pi n^3\right]$ **(2)**

IIIrly No. of available energy states within one octant of sphere of radius 'n+dn' corresponding to energy 'E+dE' $= \frac{1}{8} \times \left[\frac{4}{3}\pi (n+dn)^3\right]$ **(3)**

No. of available energy states between the shell of radius 'n' & 'n+dn' $= \frac{1}{8} \times \left[\left[\frac{4}{3}\pi (n+dn)^3\right] - \frac{4}{3}\pi n^3\right]$

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

$$\therefore \text{N(E)} = \frac{1}{8} \times \frac{4\pi}{3}\left(n^3 + dn^3 + 3n^2 dn + 3n dn^2 - n^3\right)$$

Neglecting higher power of *dn* which is very small, N (E) dE $= \frac{1}{8} \times \left[\frac{4}{3} 3n^2 dn\right]$ (or)

$$\text{N (E) dE} = \left[\frac{\pi}{2} n^2 dn\right] \quad \text{(or)} \quad \text{N (E) dE} = \left[\frac{\pi}{2} n(ndn)\right] \qquad \textbf{(4)}$$

We know that, the particle in a one dimensional box of radius 'a' in Schrödinger's wave equation is

$$E = \frac{n^2 h^2}{8ma^2} \qquad (5)$$

$$\text{(or)} \quad n^2 = \frac{8ma^2 E}{h^2} \qquad (6)$$

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(or) $n = \left[\frac{8ma^2E}{h^2}\right]^{\frac{1}{2}}$ (7)

Differentiating eqn (6) w.r.t n & E, we get $2ndn = \frac{8ma^2}{h^2}dE$ (8)

(or) $ndn = \frac{8ma^2}{2h^2}dE$ (9)

Sub the value of Eqn(4) & Eqn (7) in Eqn. (9) , we get

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

$$\text{(or) } N(E)\,dE = \frac{\pi}{2} \times \frac{1}{2} \times \left[\frac{8ma^2}{h^2}\right]^{\frac{3}{2}} \times E^{\frac{1}{2}} dE$$

Pauli's exclusion principle states that' two electrons of opposite spins can occupy each state'

$$\therefore N(E)\,dE = 2 \times \frac{\pi}{4} \times \left[\frac{8ma^2}{h^2}\right]^{\frac{3}{2}} \times E^{\frac{1}{2}} dE = \frac{\pi}{2} \times \left[\frac{2 \times 2^2 m}{h^2}\right]^{\frac{3}{2}} \times a^3 \times E^{\frac{1}{2}} dE$$

$$\therefore N(E)\,dE = \frac{4\pi}{h^3} \times (2m)^{\frac{3}{2}} \times a^3 \times E^{\frac{1}{2}} dE \quad (10)$$

Density of states is number of energy states per unit volume

$$\therefore Z(E)\,dE = \frac{N(E)dE}{V} = \frac{\frac{4\pi}{h^3} \times (2m)^{\frac{3}{2}} \times a^3 \times E^{\frac{1}{2}} dE}{a^3}$$

$$\therefore Z(E)\,dE = \frac{4\pi}{h^3} \times (2m)^{\frac{3}{2}} \times E^{\frac{1}{2}} dE \quad (11)$$

This is the density of charge carriers in the energy interval 'E' & 'E+dE'. It is used to calculate carrier concentration in metals and semiconductors.

Carrier Concentration

Normally all the energy states are not filled. Hence the probability of filling the electron is done by Fermi distribution function (E). The number of electrons per unit volume (or) density of electrons is called carrier concentration

Carrier concentration of electrons in energy bands $n_c = \int Z(E).F(E)dE$

$$\text{(or) } n_c = \frac{4\pi}{h^3} \times (2m)^{\frac{3}{2}} \times \int_{energyband} E^{\frac{1}{2}} dE.F(E) \quad (12)$$

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(or) $n_c = \frac{4\pi}{h^3} \times (2m)^{\frac{3}{2}} \times \int_{energyband} E^{\frac{1}{2}} \frac{1}{1+e^{\frac{(E-E_f)}{kT}}} dE$ (13)

n_c is known as carrier distribution function

Fermi energy at 0 Kelvin

We know that 0 K maximum energy levels that can occupied by the electron is called Fermi energy level (E_{f_0})

(i.e.,) at 0 K for $E<E_f$ and therefore F (E) = 1

∴ Integrating equation 12 within the limits 0 to E_{f_0}, then the carrier concentration is

$$n_c = \int_0^{E_{f0}} \frac{4\pi}{h^3} \times (2m)^{\frac{3}{2}} \times E^{\frac{1}{2}} dE. \quad = \quad \frac{4\pi}{h^3} \times (2m)^{\frac{3}{2}} \times \int_0^{E_{f0}} E^{\frac{1}{2}} dE.$$

(or) $n_c = \frac{8\pi}{3h^3} (2mE_{f_0})^{\frac{3}{2}}$ (14)

(or) $E_{f_0} = \left(\frac{h^2}{2m}\right) \times \left(\frac{3n_c}{8\pi}\right)^{\frac{2}{3}}$ (15)

This is the Fermi energy of electrons in solids at absolute zero. Thus, Fermi energy of a metal depends only on the density of electrons of that metal.

When the temperature increases .Fermi level (or) Fermi energy slightly decreases

It can be shown that $E_f = E_{f_0}\left[1 - \frac{\pi^2}{12}\left[\frac{kT}{E_{f_0}}\right]^2\right]$

Importance:

(i) It is the level which separates the filled valence energy level and vacant conduction energy levels

(ii) It determines the energy of the particle at any temperature

Average energy of electron s at 0K

Average energy of electron (E_{avg}) = $\frac{\text{Total energy of electrons at 0K } (E_T)}{\text{Number of Energy States at 0K } (n_c)}$ (16)

Here, Total Energy of electrons at 0K = Number of Energy states at 0K x Energy of the electron

$$E_T = \int_0^{E_{f0}} Z(E) dE.E$$

$$\therefore E_T = \frac{4\pi}{h^3} \times (2m)^{\frac{3}{2}} \int_0^{E_{f0}} E^{\frac{1}{2}}.E.dE$$

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(or) $E_T = \frac{4\pi}{h^3} \times (2m)^{\frac{3}{2}} \times \frac{E_{F_0}^{\frac{5}{2}}}{\frac{5}{2}}$

(or) $E_T = \frac{8\pi}{5h^3} \times (2m)^{\frac{3}{2}} \times E_{F_0}^{\frac{5}{2}}$ (17)

Substituting Eqn (13) & (15) in (14), we get

$$E_{Avg} = \frac{\frac{8\pi}{5h^3} \times (2m)^{\frac{3}{2}} \times E_{F_0}^{\frac{5}{2}}}{\frac{8\pi}{3h^3} (2m)^{\frac{3}{2}} \times E_{F_0}^{\frac{3}{2}}} = \frac{3}{5} E_{F_0}^{\frac{5}{2}} - E_{{}_0F}^{\frac{3}{2}}$$

∴ The average energy of electron at 0K is $E_{Avg} = \frac{3}{5} E_{f_0}$

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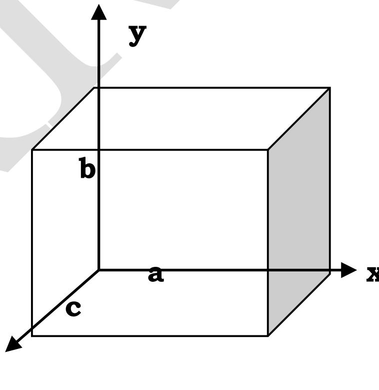
4. Derive an expression for particle in three dimensional box. What are degenerate and non-degenerate states?

The Solution of one dimensional potential box can be extended for a three dimensional potential box. Here the particle can move in any direction in space. Hence instead of one quantum number 'n' three quantum numbers n_x, n_y ,n_z are considered corresponding to the three coordinating axis (x,y,z)



Three dimensional potential box.

If a,b,c, are the length of the box as shown in figure along x,y,z axis ,then the energy of the particle $E_n = E_x + E_y + E_z$

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i.e., $E_{n_x,n_y,n_z} = \frac{n_x^2 h^2}{8ma^2} + \frac{n_y^2 h^2}{8mb^2} + \frac{n_z^2 h^2}{8mc^2}$

For a perfect cubic box a = b = c

Energy Eigen value is $E_{n_x,n_y,n_z} = \frac{h^2}{8m}\left[n_x^2 + n_y^2 + n_z^2\right]$ (1)

The corresponding normalized wave function of an electron in a cubical box can be rewritten as

$$\psi_{n_x,n_y,n_z} = \sqrt{\frac{2}{a}} \times \sqrt{\frac{2}{a}} \times \sqrt{\frac{2}{a}} \cdot \sin\frac{n_x \pi x}{a} \cdot \sin\frac{n_y \pi y}{a} \cdot \sin\frac{n_z \pi z}{a} \quad (2)$$

Degeneracy:

It is nothing but the quantum numbers having same Eigen value but different Eigen states. Such states and energy levels are called *Degenerate state*

Eg : if a state of quantum numbers are

$n_x = 1$; $n_y = 2$; $n_z = 1$, $n_x = 1$; $n_y = 1$; $n_z = 2$ &

$n_x = 2$; $n_y = 1$; $n_z = 1$ have same Eigen values as $n_x^2 + n_y^2 + n_z^2 = 6$

$$E_{121} = E_{112} = E_{211} = \frac{6h^2}{8ma^2} \quad (3)$$

But the corresponding Eigen functions are

$$\left.\begin{aligned} \psi_{121} &= \sqrt{\frac{8}{a^3}} \cdot \sin\frac{\pi x}{a} \cdot \sin\frac{2\pi y}{a} \cdot \sin\frac{\pi z}{a} \\ \psi_{112} &= \sqrt{\frac{8}{a^3}} \cdot \sin\frac{\pi x}{a} \cdot \sin\frac{\pi y}{a} \cdot \sin\frac{2\pi z}{a} \\ \psi_{211} &= \sqrt{\frac{8}{a^3}} \cdot \sin\frac{2\pi x}{a} \cdot \sin\frac{\pi y}{a} \cdot \sin\frac{\pi z}{a} \end{aligned}\right\} \quad (4)$$

(4)

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Non – Degeneracy:

For various combinations of quantum numbers if we have same energy Eigen value and Eigen function then each states and energy levels are called *Non – Degenerate state*

Eg : for $n_x = 2$; $n_y = 2$; $n_z = 2$ we have $E_{222} = \frac{12h^2}{8ma^2}$ &

$$\psi_{222} = \sqrt{\frac{8}{a^3}} \, .\sin\frac{2\pi x}{a} \, .\sin\frac{2\pi y}{a} \, .\sin\frac{2\pi z}{a}$$

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Unit I b (Part II)

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Part – A

1. What is meant by degenerate and Non - degenerate state?

For several combination of quantum numbers, if the Eigen value are same with different set of Eigen functions, such states and energy levels are called Degenerate states

For several combination of quantum numbers, if the Eigen value and Eigen functions are same, such states and energy levels are called Non - Degenerate states

2. What are the difference between quantum theory and zone theory?

S.No	Quantum Theory	Zone Theory
01.	Here the electron is assumed to move in a region of constant potential	Here the electron is assumed to move in a region of periodic potential
02.	The mass of the electron remains constant , when it moves through the constant potential	The mass of the electron varies as they move in a periodic potential called effective mass
03.	It fails to explain the classification of conductors, semiconductor and insulators	It explains the classification of conductors, semiconductor and insulators

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3. Define scattering power of the potential barrier?

It is defined as the strength with which the electrons are attracted by the positive ions and is given by $P = mV_0ba / \hbar^2$.
m – Mass of electron; *a, b* – limits with which the electrons assumed to move

4. **What is Brillouin zone?**

Brillouin zone are the boundaries that are marked by the values of propagation vector $\vec{k}$ in which the electrons can have allowed energy values without diffraction.

5. What is effective mass of electron?

When an electron is accelerated in a periodic potential within the lattice due to external electric or magnetic field, then the mass of the electron varies with respect to the applied field. This varying mass is called effective mass (m*)

6. **Will the effective mass of the electron be negative? Justify your answer?**

Yes, the effective mass of the electron can also have a negative value.
Justification: the effective mass of the electron is the mass of the electron when it is accelerated in a periodic potential and is given by $m^* = \frac{\hbar^2}{d^2E/dk^2}$

Here, $\frac{d^2E}{dk^2}$ can vary from positive to negative value. Therefore if $\frac{d^2E}{dk^2}$ is negative, then m^* will also have negative value. Also, this negative effective mass of an electron leads to the concept of hole.
Physically speaking the electrons with negative mass has same positive mass as that an electron but it has positive charge rather than negative charge

7. Explain the concept of hole and give its importance

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When the electrons are accelerated in a periodic potential, its mass varies and it moves in the direction opposite to the direction of the applied field. This variation of mass of an electron is called as negative mass behaviour of electron. The electrons with negative mass is called hole which has same positive mass as that an electron but instead of negative charge, the hole will possess positive charge.

Importance: If we have *n* number of empty states in a nearly filled band then these *n* number of empty states can be considered as *n* number of holes

8. **What are the phenomenon that explains the concept of hole?**

(i) Hall effect (ii) Thomson effect

9. **What is meant by effective mass approximation?**

For an electron moving in a constant potential field $m^* = m$. But for an electron moves in a periodic potential $m^* \neq m$. Thus, when an electron moves in a periodic potential the free electron mass *m* should be replaced by the effective mass m^* and this process is called as effective mass approximation.

10. **Compare free electron and tight binding approximations**

Sl.No	Free electron approximation	Tight binding approximation
1.	The potential energy of electron is assumed to be lesser than its total energy	The potential energy of electron is nearly equal to its total energy
2.	The width of forbidden bands are smaller than the allowed bands	The width of forbidden bands are larger than the allowed bands
3.	The interaction between neighbouring atoms will be very strong	The interaction between neighbouring atoms will be weak
4.	As the atoms come closer, the interatomic distance decreases and hence the wave function overlap with each other	As the atoms come closer, the interatomic distance increases and hence the wave function do not overlap with each other

11. **What do you understand from Fermi-Dirac statistics and what are fermions?**

(i) The particles are indistinguishable
(ii) The electrons which obey Fermi-Dirac statistics are called fermions
(iii) Each energy state can have only one particle with one spin
(iv) The number of energy states should be greater than or equal to number of particles.
(v) The total energy of the system = sum of all the energies of the particles.

12. **Compare drift velocity and thermal velocity.**

Sl.No	Drift velocity	Thermal velocity
1.	It is the average velocity acquired by the free electron in the presence of the electric field	It is the velocity of an electron without any external field
2.	The electrons moving in a direction opposite to the direction of the applied electric field.	The direction of the electrons moving with thermal velocity is random.

Part – B

1. **Explain the behaviour of an electron moving in a field of periodic potential using Kronig and Penny model?**

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Kronig and Penny treated a simplest example for one dimensional periodic potential. In this model, it assumed that the potential energy of an electron has the form of periodic array of square well as shown in figure.

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Here we are having 2 regions. viz

Region I: $0 < x < a$, here the potential energy is zero and hence the electron is assumed to be free particle. Therefore, the 1 – D schroedinger wave equation for a free particle is

$$\frac{d^2\psi}{dt^2} + \frac{2m}{\hbar^2}[E - 0]\psi = 0$$

(or) $$\frac{d^2\psi}{dt^2} + \alpha^2\psi = 0 \qquad (1)$$

Where $$\alpha^2 = \frac{2mE}{\hbar^2}$$

Allowed band

Forbidden band

+1

-3π -2π -π 0 π 2π 3π αa

-1

Region II: $-b < x < 0$, here the potential energy of the electron is V_0.

Therefore, the 1 – D schroedinger wave equation for a free particle in a periodic potential is

$$\frac{d^2\psi}{dt^2} + \frac{2m}{\hbar^2}[E - V_0]\psi = 0$$

(or) $$\frac{d^2\psi}{dt^2} - \beta^2\psi = 0 \qquad (2)$$

Where $\beta^2 = \frac{2m}{\hbar^2}[V_0 - E]$ (since $V_0 >$ E)

For both the region, the appropriate solution suggested by Bloch's is of the form is

$$\psi(x) = e^{ikx}u_k(x) \qquad (3)$$

Differentiating equation (3) and substituting it in equation (1) and (2) and then further solving it under boundary conditions, we get

$$P\frac{\sin\alpha a}{\alpha a} + \cos\alpha a = \cos ka \qquad (4)$$

Where $P = mV_0ba / \hbar^2$ is called scattering power of the potential barrier, which is the measure of the strength with which the electrons are attracted by the positive ions.

In equation (4) there are only two variables α and k. we know cos ka can take values only from -1 to 1, therefore the left hand side of equation (4) must also fall in this range. A plot is made between the LHS of equation (4) and αa for a value of $P = 3\pi/2$ (arbitrary) as shown in figure.

Conclusion

(i) The energy spectrum has a number of allowed energy bands denoted by solid horizontal line separated by forbidden band gaps denoted by dotted lines

(ii) The width of allowed energy band increases with the increase in αa

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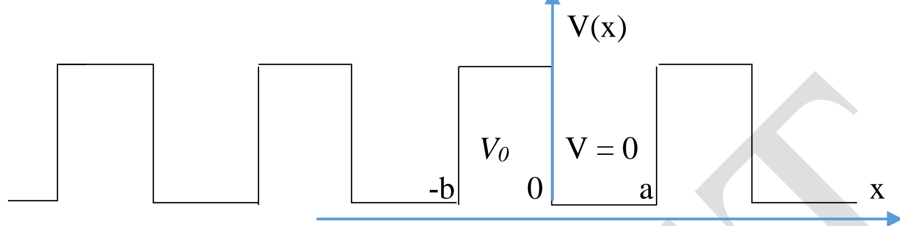
(iii) When P is increased, the binding energy of the electrons with the lattices points is also increased. Therefore the electron will not be able to move freely and hence the width of the allowed energy band is decreased. Especially for $P \rightarrow \alpha$, then allowed energy band becomes infinitely narrow and the energy spectrum becomes a line spectrum as shown in figure.

(iv) When P is decreased, the binding energy of the electron decreases and thus it moves freely over the lattice points and hence we get a wide range of allowed energy levels as shown in figure

(v) Thus by varying P from zero to infinity we get the energy spectra of all ranges.



2. Explain free electron approximation and tight binding approximation with suitable diagrams?

Free electron approximation

We know in solids there exists the ionic cores which are tightly bounded to the lattice location, while the electrons are free to move here and there throughout the solid. This is called free electron approximation.

In free electron approximation the following points are observed:

(i) The potential energy of the electron is assumed to be lesser than its total energy.

(ii) The width of the forbidden bands (E_g) are smaller than the allowed bands as shown in the figure

(iii) Therefore, the interaction between the neighbouring atoms will be very strong.

(iv) As the atoms are closer to each other, the inter atomic distance decreases and hence the wave functions overlap with each other as shown in figure

Tight binding approximation

Tight binding approximation is exactly an opposite approach of discussing the atomic arrangements, when compared to free electron approximation.

Here instead of beginning with solid core, we begin with the electrons, i.e., All the electrons are bounded to the atoms. In other way we say that the atoms are free, while the electrons are tightly bounded. Hence, this is called tight binding approximation

The following points are observed in tight binding approximation:

(i) The potential energy of the electron is assumed to be almost equal to its total energy.

(ii) The width of the forbidden bands (E_g) are larger than the allowed bands as shown in the figure

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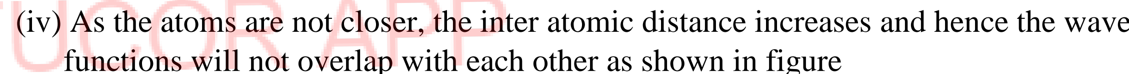
(iii) Therefore, the interaction between the neighbouring atoms will be weak.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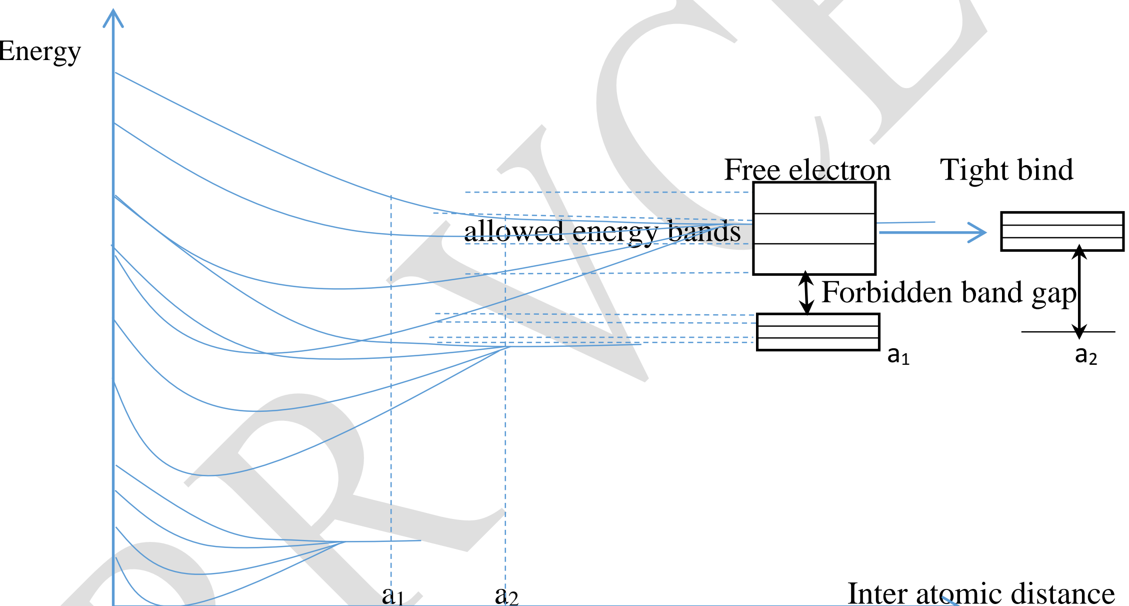
(iv) As the atoms are not closer, the inter atomic distance increases and hence the wave functions will not overlap with each other as shown in figure

Explanation

Let us consider the atoms with larger inter atomic distance (a_2) as shown in figure. Here the atoms are far apart, and all the bounded electrons have fixed energy levels. Therefore when a solid is formed by using the same element, then the energy levels occupied by the electrons in each atom will be identical, which lead to *tight binding approximation*.

Now, when we bring the atoms closer to each other to form the solid, then inter atomic distance (a_1) decreases. Therefore, the outer shell electrons begin to overlap and the energy levels also splits as shown in figure.

If the inter atomic distance is further reduced, then the splitting of energy level happens for the inner shall electrons also, which lead to *free electron approximation*.



3. **Explain zone theory and get the relationship between wave vector and the energy of the electron in a constant potential? Construct first two Brillouin zone for the electron in two dimensional lattice**

Brillouin zones *are the boundaries that are marked by the values of propagation vector* $\bar{k}$ *in which the electrons can have allowed energy values without diffraction. since k is a vector, it has different values along different directions.*

Explanation:

The relationship between the wave vector and the energy of the electron in constant potential field can be got as follows.

We know, in a length of potential box *'l'* the energy of the electron in a constant potential field.

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$$E = \frac{n^2h^2}{8ma^2} \qquad (1)$$

Also, we know that wave vector $k = \frac{n\pi}{a}$ (or) $a^2 = \frac{n^2\pi^2}{k^2}$ (2)

Substituting equation (2) in (1) we get $E = \frac{k^2h^2}{8m\pi^2}$ (3)

a plot is made between the total energy *'E'* and the wave vector *k*, for different values of *k* with $n = \pm 1$, $k = \pm\pi/a$

$n = \pm 2$, $k = \pm 2\pi/a$, *etc.*,

For the above values of *k*, the curve is obtained as shown in figure. which is in the form of a parabola with discontinuities.

From the figure it can be seen that the energy of the electron increases continuously from *0* to $\pm\pi/a$ then the electron meets the wall and is reflected. This range of allowed energy values in te region between - π/a to π/a is called first Brillouin zone. The second allowed energy values consists of two parts: one from π/a to $2\pi/a$ and another from - π/a to -2 π/a is called second Brillouin zone and so on.

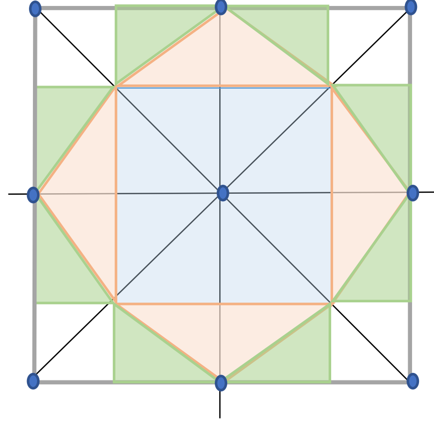
Therefore we can conclude that the electron can go from one Brillouin zone to the other only if it is supplied with an energy equal to forbidden gap energy. This forbidden gap is the one which decides whether the solid is an insulator, semiconductor (or) conductor.

Brillouin zone can be constructed by drawing vectors from the origin to the nearest lattice point and then draw Bragg planes perpendicularly between these two points. The region below this plane are said to Brillouin zone.

First Brillouin Zone ($-\pi/a$ to π/a)

Second Brillouin Zone ($-2\pi/a$ to $-\pi/a$ & $2\pi/a$ to π/a)

Third Brillouin Zone ($-3\pi/a$ to $-2\pi/a$ & $3\pi/a$ to $2\pi/a$)



4. **Define effective mass of an electron. Deduce an expression for the effective mass. Draw *E – k* curve and explain the concept of hole?**

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

When an electron of mass *m* is placed in a periodic potential and if it is accelerated with the help of an electric or magnetic field, then the mass of the electron is not constant, rather it varies with respect to the field applied. That varying mass is called as *effective mass* (m^*)

To study the effect of electric field on the motion of an electron in one dimensional periodic potential, let us consider the Brillouin zone which contains only one electron of charge *e* in

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the state k , placed in an external field *'E'*. Due to the field applied the electrons gains a group velocity quantum mechanically and therefore the acceleration changes.

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The group velocity with which the electron can travel is $V_g = \frac{d\omega}{dk}$ (1)

Where $k \rightarrow$ wave vector; $\omega \rightarrow$ angular velocity of electron $\omega = 2\pi\upsilon$ (or) $\omega = \frac{2\pi E}{h}$ (2)

Substituting equation (2) in equation (1) we get

Group velocity $V_g = \frac{2\pi}{h} \times \frac{dE}{dk}$ (or) $V_g = \frac{1}{\hbar} \times \frac{dE}{dk}$ (3)

If the electron moving in a crystal lattice with momentum *P,* then the wavelength associated is $\lambda = \frac{h}{p}$ (or) $p = \frac{2\pi}{\lambda} \times \frac{h}{2\pi}$ (or) $P = \hbar k$ (4)

Differentiating equation (4) w.r.t to t $\frac{dP}{dt} = \hbar \frac{dk}{dt}$ (5)

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

we know acceleration $a = \frac{dV_g}{dt} = \frac{d}{dt}\left[\frac{1}{\hbar} \times \frac{dE}{dk}\right]$

$$= \frac{1}{\hbar}\frac{d^2E}{dk^2} \times \frac{dk}{dt} \quad (7)$$

Substituting equation (6) in equation (7), we get

$$a_g = \frac{1}{\hbar}\frac{d^2E}{dk^2} \times \frac{F}{\hbar} \text{ (or) } a_g = \frac{1}{\hbar^2}\frac{d^2E}{dk^2}F \text{ (or) } F = \frac{\hbar^2}{d^2E/dk^2}a_g \quad (8)$$

Equation (8) resembles with newton's force equation

i.e., $F = eE = m^* a$ (9)

Where m^* is the effective mass of the electron.

Comparing equation (7) and (8), we can write $m^* = \frac{\hbar^2}{d^2E/dk^2}$ (10)

Equation (10) represents the effective mass of an electron in a periodic potential, which depend on $\frac{d^2E}{dk^2}$

Special cases:

(i) If $\frac{d^2E}{dk^2}$ is +ve, then effective mass $m^*$is also positive

(ii) If $\frac{d^2E}{dk^2}$ is -ve, then effective mass $m^*$is also negative

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(iii) If $\frac{d^2E}{dk^2}$ is zero, then effective mass m^* becomes infinity

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Negative effective mass (or) concept of hole

To show that the effective mass has negative value. Let us take the Energy - wave vector (*E-k*) of a single electron in a periodic potential. i.e., consider the 1st Brillouin zone (allowed energy band) alone as shown in figure.

In the $E-k$ curve, the band can be divided in to two bands *viz.* upper band and lower band with respect to a point (P) called a **Point of inflection**.

(i) In the **lower band** the value of $\frac{d^2E}{dk^2}$ is a decreasing function from the point of inflection

$\therefore \frac{d^2E}{dk^2}$ is $+ve$ and hence m^* should be $+ve$ in the lower band. If a plot is made between m^* and k for different values of $\frac{d^2E}{dk^2}$, we get the curve as shown in figure

(ii) In the **Upper band** of E - k the value of $\frac{d^2E}{dk^2}$ is a increasing function from the point of inflection

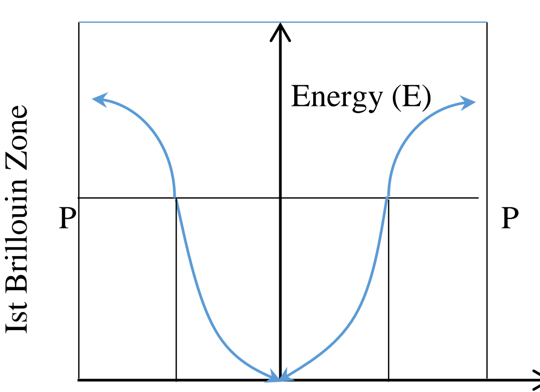
$\therefore \frac{d^2E}{dk^2}$ is -ve and hence m^* should be -ve in the upper band. If a plot is made between m^* and k for different values of $\frac{d^2E}{dk^2}$, we get the curve as shown in figure

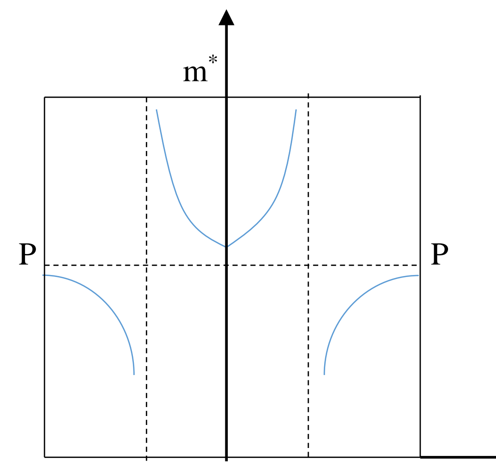
(iii) **At the point of inflection,** the value of $\frac{d^2E}{dk^2} = 0$ and hence in m^* - k plot, effective mass goes to infinity.

The electron with the negative effective mass is called **Hole**, in other words the electron in the upper band which behaves as a positively charged particle is called hole. It has the same mass as that of an electron but with positive charge.

Therefore, the advantage of the concept of hole is, for a nearly filled band with n number of empty states as shown in figure n number of holes arises

In other words, we can say that the presence of hole is attributed to an empty state, for an electron to be filled. Thus, based on the hole concept several phenomena like Thompson effect, Hall effect, etc., are well explained.





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-π / a   - k_0 O k_0 π / a K π/a   - k_0 O k_0 π/a K

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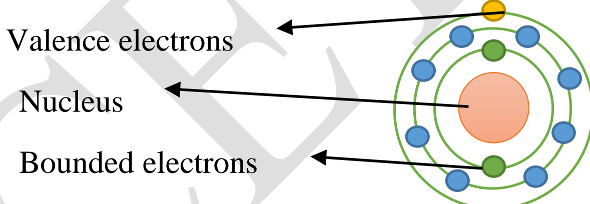
5. Discuss qualitatively how band theory of solids leads to the classification of solids into conductors, semiconductors and insulators

(i) Free and bound electrons

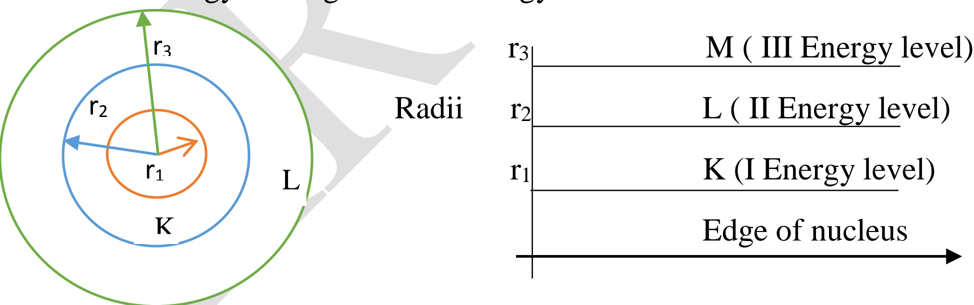
In an isolated atom all the electrons are tightly bounded with the central positive nucleus and revolves around various orbits. The number of electrons the outermost orbit are called *valence electrons*. In the outermost orbits, the attractive force between the nucleus and electrons will be very less, so that the electrons can be easily detached from the nucleus. These detached

electrons from the outermost orbits are called *free electrons*. But as far as the innermost orbits are concerned, the electrons are tightly bounded with positive nucleus, and hence they are termed as *bound electrons*.



(ii) Energy levels

We know that each orbit of an atom has fixed amount of energy associated with it. The electrons moving in a particular orbit possess the energy of that orbit. The larger the orbit, the greater is its energy. So, the outermost orbit electrons possess more energy than the inner orbit electrons. A convenient way of representing the energy of different orbits are called *energy levels* as shown in figure. Let E_1 be the energy level of K shell, E_2 be the energy level of L shell, E_3 be the energy level of M shell and so on. The larger the orbit of an electron, the greater is its energy and higher is the energy level.



From the figure it is clear that the electrons can revolve only in certain permitted orbits of radii r_1, r_2 *and* r_3 *etc.*, and not in any arbitrary orbit. Since the electrons are not allowed in between the radii r_1 *and* r_2 or between the radii r_2 *and* r_3 etc., there won't be any electronic energy levels in between those radii so called *forbidden radii.* These unallowed energy levels are called *forbidden energy levels.*

(iii) Energy bands

It has to be noted that as long as the atoms are widely separated, they have identical energy levels. But, once the atoms are brought together the interatomic force of attraction between the atoms in the solid may modify the energy levels of a solid as energy bands. Now let us discuss how energy levels of single free atom becomes bands in solids.

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Let us consider two identical atoms of diameter (d) separated at a distance (r), so that the electronic energy levels of one atom [E_1^1(*K – shell*) *and* E_2^1(*L – shell*)] do not affect the electronic energy levels of the other atom [E_1^2(*K – shell*) *and* E_2^2(*L – shell*)] as shown in figure

L – shell E_2^2

L – shell E_2^1 L – shell E_2^2 L – shell E_2^1

K – shell E_1^1 K – shell E_1^2 K – shell E_1^2

K – shell E_1^1

Atom1 d Atom 2 d

r>>d r = d

Now when the atoms are bring closer to each other, some force of attraction occurs between them and according to quantum mechanics, their wave functions will start overlapping. Therefore when two atoms are brought closer, it does not remains as two independent atoms, rather it forms a **single two – atom** system with two different energy levels to form energy band as shown in figure.

Origin of energy band formation in solids

We know that when two atoms of equal energy levels are brought closer to eachother, the original energy levels *viz* E_1 *and* E_2 splits each into two energy levels. i.e., the *K*- shell energy E_1 splits in to E_1^1 *and* E_2^1. Similarly the *L* – shell energy E_2 splits in to E_1^2 *and* E_2^2. *Now when* three atoms are brought closer together, the original energy levels *viz* E_1 and E_2 splits each into three energy levels *viz* E_1^1 E_1^2 *and* E_1^3*and* E_2^1 E_2^2 *and* E_2^3respectively. These type of transformations from the original energy levels into two (or) more energy levels is known as *Energy level splitting*

Energy bands

Therefore, if '*N*' number of atoms of equal energy levels are brought closer to from a solid, then it forms a closely spaced continuous energy levels, so called **energy bands**.

Hence an energy band can be defined as, *the range of energies possessed by an electron in a solid*. The magnified view of the energy band which consists of a large number of very closely spaced energy levels as shown in figure.

Inner Filled Bands, Valence band and Conduction band

During the formation of energy bands, the inner filled energy levels forms a energy band called *Inner filled bands*. Similarly the electrons in the outermost shells of atoms forms an energy band called *valence band*. The valence band will be of completely filled (or) partially filled with electrons, based on the type of materials.

If an electron comes out from valence band for conduction, then they form an energy level corresponding to the energy band called *conduction band*

Forbidden gap

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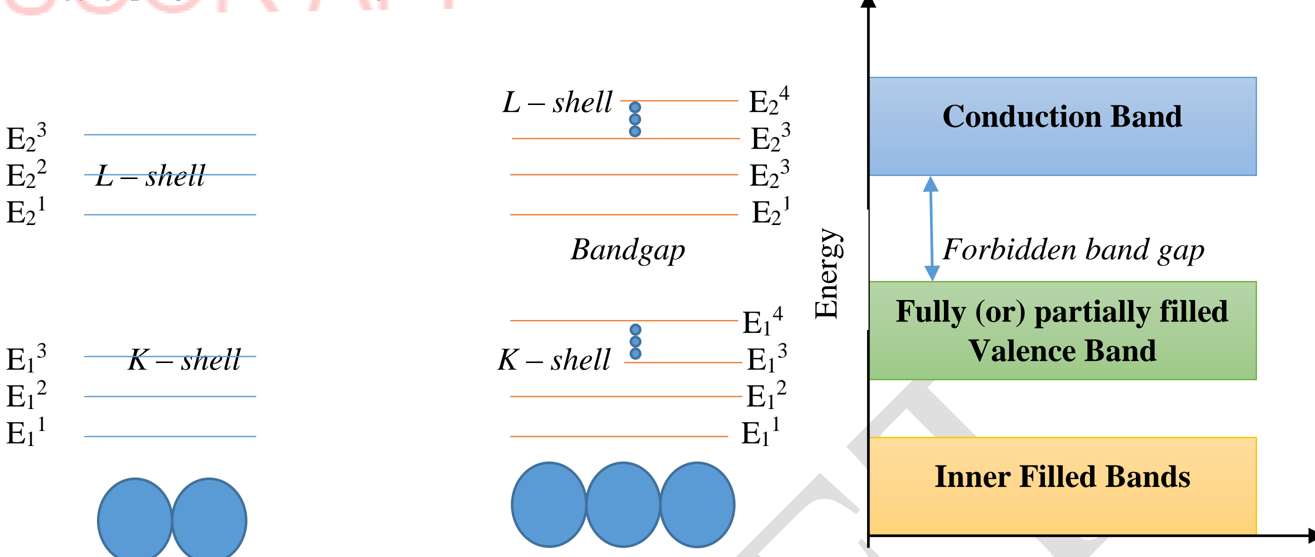
While referring to energy bands, they are separated by small regions which does not allow any energy levels. Such regions between the energy bands are called forbidden gaps (or) forbidden energy gap E_g as shown in figure.



Based on band theory and the presence of forbidden band gap the materials are classified in to three categories viz:

(i) **Metals (or) Conductors**

Here, there is no forbidden band gap. Hence the valence band and conduction band overlap with each other. Since the free electron are relatively available in large number, even a small external field induces the electrons from the valence band to conduction band and hence conduction easily occurs.

Example: Copper, Aluminium, etc.

(ii) **Semiconductors**

Here, the forbidden band gap is small (say 0.5 to 1.5 eV) and hence the width of forbidden gap is smaller than allowed energy bands. Generally, the free electrons in valence band is comparatively less compared to conductors because of finite forbidden gap and hence the semiconductor requires external field with energy greater than or equal to this forbidden gap energy such that conduction process occurs.

Example: Germanium, Silicon, etc.

(iii) **Insulators**

Here the width of the forbidden gap is wider (say 3 to 5.47 eV) and hence the width of forbidden gap is larger than allowed energy bands. Therefore in case of insulator, a sufficiently large energy is required for conduction to occur.

Example: Diamond, Dielectrics, etc,

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2. Semiconducting Materials

Part – A

1. State the properties of semiconductor?

(i) The resistive lies between 10^{-4} to 0.5 Ωm

(ii) At 0K, they behave as insulator

(iii) The conductivity of the semiconductor increases both due to the temperature & impurity

(iv) They have negative temperature coefficient of resistance

(v) In semiconductors both the electron and holes are charge carriers and will take part in conduction.

(vi) They are formed by covalent bonds

2. What are elemental and compound semiconductor? Give Example?

Elemental semiconductors (Indirect Band gap Semiconductors) are made from single element of fourth group elements of the periodic table.

Eg: Silicon, Germanium

Semiconductors (Indirect Band gap Semiconductors) which are formed by combining third and fifth group elements or second and sixth group elements of the periodic table are called compound semiconductors.

Eg: GaAs, InP, MgO, ZnS, etc.,

3. Differentiate Indirect and Direct Band gap semiconductor?

S.No	Indirect Bandgap Semiconductor	Direct Bandgap Semiconductor
1.	Heat produced during recombination	Photons emitted during recombination
2.	Life time of charge carriers is more	Life time of charge carriers is less
3.	They are used as diodes, transistors, etc.,	They are used as LED's, Laser diodes and IC's, etc.,
4.	Current amplification is more	Current amplification is less

4. What is meant by intrinsic and extrinsic semiconductor?

S.No	Intrinsic Semiconductor	Extrinsic Semiconductor
1.	It is the purest form of Semiconductor	It is due to adding Impurities to semiconductor
2.	Charge carriers are only due to thermal agitation	Charge carriers are due to impurities and thermal agitation
3.	They have low electrical conductivity	They have high electrical conductivity
4.	They have low operating temperature	They have low operating temperature
5.	At 0K, Fermi energy lies between	At 0K, Fermi energy is close to

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	valence band & conduction band	conduction band in 'n' type semiconductor & close to valence band in 'p' type semiconductor

5. Define Fermi level in semiconductors? Mention its position in intrinsic & Extrinsic Semiconductor?

Fermi level is the energy level which separates the filled and empty energy states

Intrinsic Semiconductor: Here the Fermi level exactly lies between lowest energy level of conduction band and highest energy level of valence band $E_F = \frac{E_c + E_v}{2}$

'N-type Semiconductor' the Fermi energy lies exactly between minimum energy level of conduction band and donor energy level $E_F = \frac{E_c + E_d}{2}$

'P-type Semiconductor' the Fermi energy lies exactly between the acceptor energy level and the maximum energy level of valence band $E_F = \frac{E_c + E_a}{2}$

6. Define Hall Effect and Hall Voltage?

When a conductor carrying a current (I) is placed in a transverse magnetic field (B), a potential difference (Electric field) is produced inside the conductor in a direction normal to the direction of both the current and magnetic field. This phenomenon is known as **Hall Effect** and the generated voltage is called **Hall voltage**

7. State the law of mass action in semiconductor?

The product of electron & hole concentration remains constant at a given temperature and is equal to the square of intrinsic carrier concentration i.e., $n_i.n_e = n_i^2$

8. What are the applications of Hall Effect?

(i) It is used to determine whether the material is p-type or n- type semiconductor

(ii) It is used to find carrier concentration

(iii) It is used to determine the sign of the current carrying charges

(iv) It is used to measure magnetic flux density using a semiconductor sample of known hall coefficient.

9. Mention any four advantages of semiconducting materials?

(i) It can behave as insulators at 0K and as conductors at high temperature

(ii) They posses crystalline structure

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(iii) N-type & p-type semiconductors are prepared by adding impurities with the charge carriers of electrons and holes respectively.

(iv) They find applications in manufacturing Diodes, Transistors, IC's , etc.,

10. Write an expression for carrier concentration in intrinsic semiconductor?

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

Where m_e^* - Effective mass of electron; m_h^* - Effective mass of hole; E_g – Band gap

11. Write an expression for carrier concentration in n - type semiconductor?

Carrier concentration of n – type semiconductor is $n_i = [2N_d]^{\frac{1}{2}}\left[\frac{2\pi m_e^* kT}{h^2}\right]^{\frac{3}{4}} e^{\left[\frac{E_d - E_c}{2kT}\right]}$

Where m_e^* - Effective mass of electron; N_d – donor concentration; E_d- donor energy level;

E_c – Energy level in conduction band

12. Write an expression for carrier concentration in p - type semiconductor?

Carrier concentration of n – type semiconductor is $n_i = [2N_a]^{\frac{1}{2}}\left[\frac{2\pi m_h^* kT}{h^2}\right]^{\frac{3}{4}} e^{\left[\frac{E_v - E_a}{2kT}\right]}$

Where m_e^*- Effective mass of electron; N_a – acceptor concentration; E_a- acceptor energy level; E_v – Energy level in valence band.

13. Define donors and acceptors and state its ionization energy?

Donors are the penta valent atoms which donates electrons to the pure semiconductors. The energy required to donate an electron from donor energy level to the conduction band by $\Delta E = E_c - E_d$ is called ionization energy of donor

Acceptors are the trivalent atoms which accept electrons from the pure semiconductor. The energy required to move an electron from valence band to acceptor energy level by $\Delta E = E_a - E_v$ is called ionization energy of acceptor.

Part – B

1. Derive an expression for the intrinsic carrier concentration of a semicondcutor?

The number of charge carriers per unit volume of the material is called carrier concentration or density of charge carriers

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Electrons in Conduction Band

The number of electrons whose energy lies in the range "E" & "E+dE" in the conduction band is given by dn } = Z (E) F (E) dE (1)

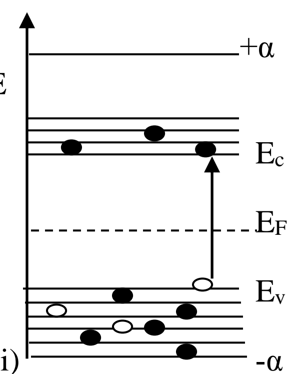
Where Z (E) – density of states in the energy ranges 'E' &'E + dE'
F (E) – Probability of number of electron occupying in the conduction band

The number of electrons in the conduction band for the entire region is calculated by integrating equation (1) from top energy level 'E_c' to bottom energy level 'α'

i.e., $n = \int_{E_c}^{\infty} Z(E)F(E)dE$ (2)

W.K.T, Density of states in the conduction band in the energy range 'E' & 'E+dE' is given by } $Z(E)\,dE = \frac{4\pi}{h^3}(2m)^{\frac{3}{2}} E^{\frac{1}{2}} dE$ (3)

The bottom edge of the conduction band (E_c) represents the potential energy of an electron at rest. Therefore, (E - E_c) is the kinetic energy of the conduction electron at higher energy levels. Therefore the equation (3) is modified as



Fig(i)

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

Since the electron is moving in a periodic potential, its mass m is replaced by its effective mass m_e^*.

The probability of electron occupancy is given by $F(E) = \frac{1}{1 + e^{(E-E_F)/kT}}$ (5)

Substituting (4) & (5) in (2), we get, $n = \int_{E_c}^{\infty} \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}}(E - E_c)^{\frac{1}{2}} \times \frac{1}{1 + e^{(E-E_F)/kT}} dE$ (6)

For all possible temperature, $E - E_F >> kT$, hence in the denominator, $1 + e^{\frac{E-E_F}{kT}} \cong e^{\frac{E-E_F}{kT}}$

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

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

(or) $$n = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}} e^{E_F/kT} \int_{E_c}^{\infty} (E - E_c)^{\frac{1}{2}} e^{-E/kT} dE \quad (7)$$

To solve this, assume the following:

E - $E_c = x$	$E = E_c$	$E = +\alpha$
$E = E_c + x$	E_c - $E_c = x$	$\alpha - E_c = x$
$dE = dx$	$x = 0$	$x = \alpha$

Now, $$n = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}} e^{E_F/kT} \int_{0}^{\infty} x^{\frac{1}{2}} e^{-(E_c + x)/kT} dx$$

(or) $$n = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}} e^{(E_F - E_c)/kT} \int_{0}^{\infty} x^{\frac{1}{2}} e^{-x/kT} dx \quad (8)$$

Using gamma function, $\int_{0}^{\infty} x^{\frac{1}{2}} e^{-x/kT} dx = \frac{(kT)^{\frac{3}{2}} \pi^{\frac{1}{2}}}{2}$ (9)

Substituting eqn (9) in (8), we get, $n = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}} e^{(E_F - E_c)/kT} \times \frac{(kT)^{\frac{3}{2}} \pi^{\frac{1}{2}}}{2}$

(or) $$\boxed{n = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} e^{(E_F - E_C)/kT}} \quad (10)$$

This is the expression of electrons in the conduction band of an intrinsic semiconductor.

Concentration of holes in the Valence band

We know that if an electron is transferred from valence band to conduction band, a hole is created in valence band. Let dp be the number of holes in the valence band for the energy range E & $E+dE$. $\therefore dp$ = Z (E) (1 – F (E)) dE (1)

Where Z (E) – Density of states in the energy range E & E+dE

(1 – F(E)) – Probability of unoccupied (vacant) electron state (presence of hole) in valence band

$$\therefore (1 - F(E))\, dE = 1 - \frac{1}{1 + e^{(E - E_F)/kT}} = \frac{1 + e^{(E - E_F)/kT} - 1}{1 + e^{(E - E_F)/kT}} = \frac{e^{(E - E_F)/kT}}{1 + e^{(E - E_F)/kT}} \quad (2)$$

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$\because$ E < E_F in valence band, (E – E_F) has negative quantity & hence in denominator $e^{(E-E_F)/kT}$ is very small when compared with 1, hence $1+e^{(E-E_F)/kT} \cong 1$

$$\therefore 1-F(E)=e^{(E-E_F)/kT} \qquad (3)$$

E_v is the top level in the valence band and having potential energy of a hole at rest. Hence

$(E_v - E)$ is the kinetic energy of the hole at level below E_V. Hence,

Density of states in the valence band is $Z(E)dE=\frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}}(E_V-E)^{\frac{1}{2}}dE$ (4)

Where, m_h^* - effective mass of the hole in the valence band

Substituting equation (4), (3) in (1), we get, $dp=\frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}}(E_V-E)^{\frac{1}{2}}e^{(E-E_F)/kT}dE$ (5)

The number of holes in the valence band for the entire energy range is obtained by integrating

Above equation between the limits –α to E_V

i.e., $\int dp=\int_{-\infty}^{E_V}\frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}}(E_V-E)^{\frac{1}{2}}e^{(E-E_F)/kT}dE$

(or) $$dp=\frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}}e^{-E_F/kT}\int_{-\infty}^{E_V}(E_V-E)^{\frac{1}{2}}e^{E/kT}dE \qquad (6)$$

To solve this, assume the following:

E_v - $E = x$	E = - α	$E = E_v$
$E = E_v$ - x	E_v -(- α) = x	E_v– $E_v = x$
dE = - dx	x = α	$x = 0$

$$p=\frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}}e^{-E_F/kT}\int_{\infty}^{0}x^{\frac{1}{2}}e^{-(x+E_v)/kT}(-dx)$$

(or) $$p=\frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}}e^{(E_v-E_F)/kT}\int_{0}^{\infty}x^{\frac{1}{2}}e^{-x/kT}dx \qquad (7)$$

Using gamma function, $\int_{0}^{\infty}x^{\frac{1}{2}}e^{-x/kT}dx=\frac{(kT)^{\frac{3}{2}}\pi^{\frac{1}{2}}}{2}$ (8)

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Substituting eqn (8) in (7), we get, $p = \frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}} e^{(E_v - E_f)/kT} \times \frac{(kT)^{\frac{3}{2}} \pi^{\frac{1}{2}}}{2}$

(or) $$p = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}} e^{(E_v - E_F)/kT} \quad (9)$$

This is the expression of holes in the valence band of an intrinsic semiconductor

Intrinsic Carrier Concentration:

In intrinsic semiconductor, carrier concentration of electrons in conduction band (n_i) =

carrier concentration of holes in valence band n_p &

hence the intrinsic carrier concentration is $n_i^2 = n_i \times n_p$

$$n_i^2 = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} e^{(E_F - E_C)/kT} \times 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}} e^{(E_v - E_F)/kT} \quad (1)$$

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

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

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

Where $E_c - E_v = E_g$ is the forbidden energy gap.

2. Discuss the variation of Fermi Level with temperature in an intrinsic semiconductor?

We know that, for an intrinsic semiconductor, the density of electron in the conduction band is equal to the density of holes in the valence band.

i.e., $n_i = n_p$ (1)

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

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Rearranging, we get, $e^{(E_F - E_C)/kT} = \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} e^{(E_v - E_F)/kT}$

(or) $e^{(2E_F)/kT} = \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} e^{(E_v + E_c)/kT}$

Taking log on both sides, we get

$$\log_e e^{(2E_F)/kT} = \log_e \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} + \log_e e^{(E_v + E_c)/kT}$$

(or) $\frac{2E_F}{kT} = \frac{3}{2}\log_e \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} + \frac{E_v + E_c}{kT}$

(or) $E_F = \frac{kT}{2}\left[\frac{3}{2}\log_e \left(\frac{m_h^*}{m_e^*}\right) + \frac{E_v + E_c}{kT}\right] = \frac{3kT}{4}\log_e \left(\frac{m_h^*}{m_e^*}\right) + \frac{kT}{2}\left[\frac{E_v + E_c}{kT}\right]$

(or) $\boxed{E_F = \frac{3kT}{4}\log_e \left(\frac{m_h^*}{m_e^*}\right) + \left[\frac{E_v + E_c}{2}\right]}$ (2)

If $m_e^* = m_h^*$, then $\log_e \left(\frac{m_h^*}{m_e^*}\right) = \log_e 1 = 0$,

hence the above equation becomes, $E_F = \left[\frac{E_v + E_c}{2}\right]$ (3)

Thus, the Fermi level is located half way between the top of the valence band and bottom of the conduction band. Its position is independent of temperature. If $m_e^* < m_h^*$,thus, the Fermi level is just above the middle of energy gap and its rises slightly with increasing temperature.

3. Discuss the carrier concentration, the variation of Fermi level with temperature in the case of n –type semiconductors for low doping level?

In n –type semiconductor, the donor level is just below the conduction band. N_d denotes the donor concentration & E_d represents the energy of the donor level.

Density of electrons per unit volume in the conduction band is given by

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

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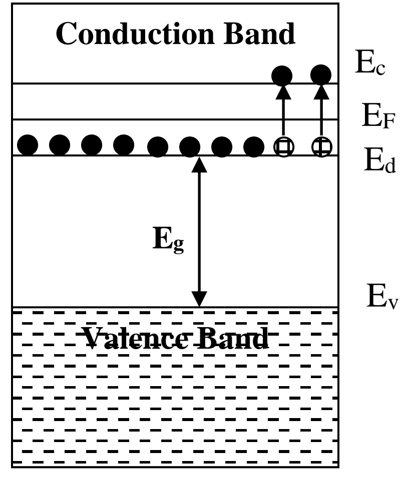
here E_f – Fermi energy; E_c – Energy corresponding to the bottom of the conduction band



Density of the ionized donors = $N_d\,[1 - F(E)]$

$$= N_d\left[1 - \frac{1}{1 + e^{(E_d - E_F)/kT}}\right]$$

$$= N_d\left[\frac{1 + e^{(E_d - E_F)/kT} - 1}{1 + e^{(E_d - E_F)/kT}}\right]$$

$$= N_d\left[\frac{e^{(E_d - E_F)/kT}}{1 + e^{(E_d - E_F)/kT}}\right]$$

Density of ionized donors $= \left[\frac{N_d}{\frac{1 + e^{(E_d - E_F)/kT}}{e^{(E_d - E_F)/kT}}}\right] = \left[\frac{N_d}{1 + e^{(E_F - E_d)/kT}}\right]$ (2)

At equilibrium, the density of electrons in conduction band = Density of ionized donors.

Equating (1) & (2), $2\left[\frac{2\pi m_e^* kT}{h^2}\right]^{\frac{3}{2}} e^{(E_F - E_c)/kT} = \frac{N_d}{1 + e^{(E_F - E_d)/kT}}$ (3)

E_F lies more than few kT above donor levels, hence $e^{(E_d - E_F)/kT}$ is large compared to '1'. Hence the '1'' in denominator of R.H.S of equation (3) is neglected.

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

(or) $2\left[\frac{2\pi m_e^* kT}{h^2}\right]^{\frac{3}{2}} e^{(E_F - E_c)/kT} = N_d e^{(E_d - E_F)/kT}$ (4)

Taking log on both sides,

$$\log\left[2\left[\frac{2\pi m_e^* kT}{h^2}\right]^{\frac{3}{2}}\right] + \log_e e^{(E_F - E_c)/kT} = \log_e N_d e^{(E_d - E_F)/kT}$$

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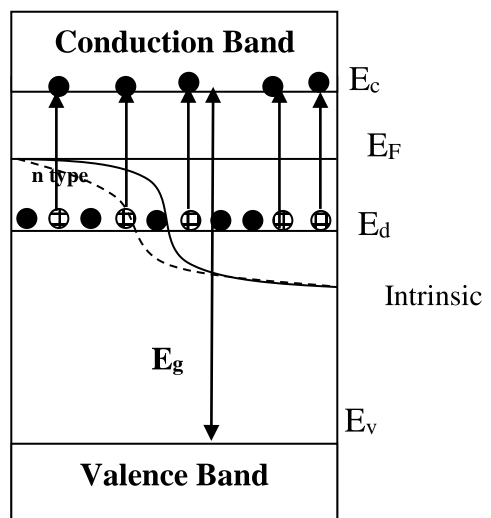
$$\text{(or)}\ \log\left[2\left[\frac{2\pi m_e^* kT}{h^2}\right]\right]^{\frac{3}{2}} + \frac{E_F - E_c}{kT} = \log N_d + \frac{E_d - E_F}{kT} \qquad (5)$$



$$\text{(or)}\ \frac{E_F - E_c - E_d + E_F}{kT} = \log N_d - \log\left[2\left[\frac{2\pi m_e^* kT}{h^2}\right]^{\frac{3}{2}}\right]$$

$$\text{(or)}\ \frac{2E_F - E_c - E_d}{kT} = \log\left[\frac{N_d}{2\left[\frac{2\pi m_e^* kT}{h^2}\right]^{3/2}}\right]$$

$$\text{(or)}\ 2E_F = E_d + E_c + kT\log\left[\frac{N_d}{2\left[\frac{2\pi m_e^* kT}{h^2}\right]^{3/2}}\right]$$

$$\text{(or)}\ E_F = \frac{E_d + E_c}{2} + \frac{kT}{2}\log\left[\frac{N_d}{2\left[\frac{2\pi m_e^* kT}{h^2}\right]^{3/2}}\right] \qquad (6)$$

Substituting the expression of E_F from (6) in (1), we get

$$n = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} \exp\left[\frac{\left(\frac{E_d + E_c}{2} + \frac{kT}{2}\log\left[\frac{N_d}{2\left[\frac{2\pi m_e^* kT}{h^2}\right]^{3/2}}\right]\right) - E_c}{kT}\right] \qquad (7)$$

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

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

$$n = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} \frac{\left[\frac{N_d}{2}\right]^{1/2}}{\left[\frac{2\pi m_e^* kT}{h^2}\right]^{3/4}} e^{(E_d - E_c)/2kT} \quad (8)$$

Rearranging the expression (8), we have

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

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

Where ▲E= E_c - E_d is the ionization energy to transfer Energy from donor energy level to the conduction band.

Results:

(i) The density of electrons is proportional to square root of donor concentration and valid at low temperature alone

(ii) At high temperature, intrinsic carrier concentration must take along with this concentration

Variation of Fermi level with temperature and impurity concentration

Fermi level of n – type semiconductor is $$E_F = \frac{E_d + E_c}{2} + \frac{kT}{2}\log\left[\frac{N_d}{2\left[\frac{2\pi m_e^* kT}{h^2}\right]^{3/2}}\right] \quad (1)$$

At T = 0K, the above equation reduces to $$E_F = \frac{E_d + E_c}{2} \quad (2)$$

(i) At 0K, Fermi level lies exactly at the centre of the donor level and bottom of the conduction band.

(ii) As the temperature is gradually increased from a low temperature, the contribution of electron increases and at very high temperature, it far exceeds the donor concentration and the intrinsic behaviour predominates at higher temperature.

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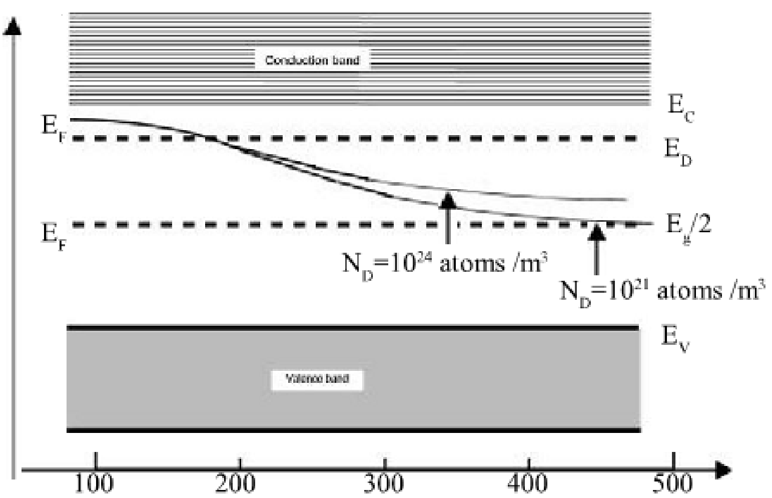
(iii) Fermi level shifts downwards when the temperature is increased and finally reaches the middle of the band gap (or) intrinsic Fermi level.

(iv) Further when the concentration of donors increases, the extrinsic behaviour also extends up to very high temperature & Fermi level reaches the middle of the band gap only at high temperature.



4.Discuss the carrier concentration, the variation of Fermi level with temperature in the case of p –type semiconductors for low doping level?

In p – type semiconductor, the acceptor energy level is just above the valence band. Let E_a represents the energy of the acceptor level and N_a represents the number of acceptor atoms per unit volume.

Density of holes per unit volume in valence band is given by $p = 2\left[\frac{2\pi m_h^* kT}{h^2}\right]^{\frac{3}{2}} e^{(E_v - E_F)/kT}$ (1)

Where E_v is the energy corresponding to the top of the conduction band

Density of the ionized acceptors = $N_a F(E_a) = \frac{N_a}{1 + e^{(E_a - E_F)/kT}}$ (2)

Since $E_a - E_F$ is very large when compared to kT. $e^{(E_a - E_F)/kT}$ is a large quantity and thus '1' in denominator of R.H.S of equation(2) is neglected. hence, equation(2), reduces to

$$N_a F(E_a) = \frac{N_a}{e^{(E_a - E_F)/kT}} = N_a e^{(E_F - E_a)/kT} \quad (3)$$

At equilibrium, the density of holes in Valence band = Density of ionized acceptors

$$2\left[\frac{2\pi m_h^* kT}{h^2}\right]^{\frac{3}{2}} e^{(E_v - E_F)/kT} = N_a e^{(E_F - E_a)/kT} \quad (4)$$

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Taking log on both sides,

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

$$\text{(or)}\ \log\left[2\left[\frac{2\pi m_h^* kT}{h^2}\right]^{\frac{3}{2}}\right] + \frac{E_v - E_F}{kT} = \log N_a + \frac{E_F - E_a}{kT} \qquad (5)$$

Rearranging the expression (5), we have

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

(or) $$\frac{2E_F - (E_a + E_v)}{kT} = -\log_e\left\{\frac{N_a}{\left[2\left[\frac{2\pi m_h^* kT}{h^2}\right]^{\frac{3}{2}}\right]}\right\}$$

(or) $$2E_F = (E_a + E_v) - kT\log_e\left\{\frac{N_a}{\left[2\left[\frac{2\pi m_h^* kT}{h^2}\right]^{\frac{3}{2}}\right]}\right\}$$

(or) $$E_F = \frac{(E_a + E_v)}{2} - \frac{kT}{2}\log_e\left\{\frac{N_a}{\left[2\left[\frac{2\pi m_h^* kT}{h^2}\right]^{\frac{3}{2}}\right]}\right\} \qquad (6)$$

Sub. The expression of E_F in equation (6), we get

$$p = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}} \exp\left[\frac{\left(E_v - \frac{E_v - E_a}{2} + \frac{kT}{2}\log\left[\frac{N_a}{2\left[\frac{2\pi m_h^* kT}{h^2}\right]^{3/2}}\right]\right)_c}{kT}\right] \qquad (7)$$

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(or) $$p = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}} \exp\left[\left(\frac{2E_v - E_v - E_a}{2kT} + \frac{1}{2}\log\left[\frac{N_a}{2\left[\frac{2\pi m_h^* kT}{h^2}\right]^{3/2}}\right]\right)\right] \quad (8)$$

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

(or) $$p = (2N_a)^{1/2}\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/4} e^{(E_v - E_a)/2kT} \quad (9)$$

If $E_a - E_v = \Delta E$ is the acceptor ionization energy required to move the electron from valence band to acceptor energy level, then equation (9) becomes,

$$p = (2N_a)^{1/2}\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/4} e^{-\Delta E/2kT} \quad (10)$$

Results:

(i) Density of holes in valence band is proportional to square root of acceptor concentration

(ii) At very high temperature p – type semiconductor behaves like an intrinsic semiconductor

Variation of Fermi level with temperature

We know that $$E_F = \frac{(E_a + E_v)}{2} - \frac{kT}{2}\log_e\left\{\frac{N_a}{\left[2\left[\frac{2\pi m_h^* kT}{h^2}\right]^{\frac{3}{2}}\right]}\right\} \quad (1)$$

At T = 0K , the above expression becomes, $$E_F = \frac{E_a + E_v}{2} \quad (2)$$

(i) At 0K the Fermi level lies exactly halfway between acceptor level E_a and top of the valence band E_v

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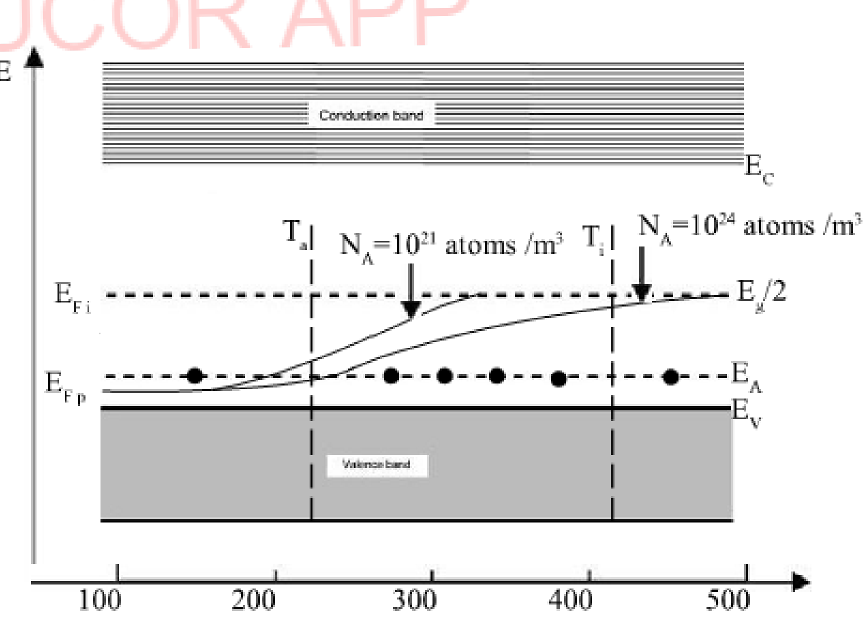

(ii) As the temperature increases, the Fermi level shifts upwards, at a particular temperature, when all the acceptor atoms are ionized and Fermi level crosses the acceptor level

(iii) At very high temperature, the Fermi level is shifted to intrinsic Fermi level and behave as intrinsic semiconductor

5. What is Hall Effect? Derive an expression of hall coefficient? Describe an experimental setup for the measurement of hall coefficient?

"*When the conductor carrying a current (I) is placed in a perpendicular magnetic field (B), a potential difference is developed inside the conductor in a direction normal to the directions of both the current and magnetic field*"

This phenomenon is known as Hall Effect and the corresponding voltage thus generated is called Hall voltage

Explanation

Consider an external field applied along the X-axis of the specimen. Assuming that the material is *n*-type semiconductor, the current flow consists mainly of electrons moving from right to left, corresponding to the conventional current direction.

When this specimen is placed in a magnetic field 'B' and if 'v' is the velocity of the electrons perpendicular to the magnetic field then each one of them will a experience a downward force of magnitude Bev

This downward force (Lorentz Force F_L) due to magnetic field causes the electrons to be deflected in the downward direction and hence there is an accumulation of negative charges on

the bottom face of the slab. This causes the bottom face of the slab to be more negative with respect to the top face and a potential difference is established from top to bottom of the specimen. This potential difference causes a field E_H called Hall field in negative y direction. There is a force eE_H acting on the electron in the upward direction due to this field.

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Theory of Hall Effect

At equilibrium, the downward force Bev will balance the upward force eE_H

$Bev = eE_H$ (1)

In a uniform sample, the electric current density (J) is related to the drift velocity as

$J = -neV$

Where n is the concentration of electrons.

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

Substituting equation (2) in (1),

$$E_H = \frac{-BJ}{ne}$$

Current

Y

V_H

X

Z

Magnetic field

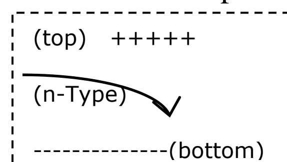
This can be written as $E_H = BJR_H$ (4)

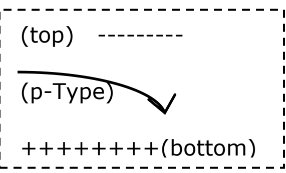
Where R_H = - 1 / ne is called Hall coefficient

The negative sign indicates that the developed field is in the negative y direction.

III^{rly}, the Hall coefficient for p – type semiconductor is R_H = 1 / p e.

Where p is the concentration of holes





Determination of Hall coefficient

The hall field per unit current density per unit magnetic induction is defined as hall coefficient.

If t is the thickness of the sample and V_H is the hall voltage, then $V_H = E_H\, t$ (5)

Where E_H is hall field.

From equation (4), we get $E_H = R_H J_x B$

Substituting the value of (5) in above equation, we get $V_H = R_H J_x B\, t$ (6)

Now the current density J_x can be written as $J_x = \frac{I_x}{bt}$ (7)

Where 'b ' is the width and bt is the area of cross section of the sample

Substituting equation (7) in equation (6), we get $V_H = \frac{R_H I_x Bt}{bt}$

$$V_H = \frac{R_H I_x B}{b} \quad (8)$$

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(or) $$R_H = \frac{V_H b}{I_X B} \qquad (9)$$

For an n – type semiconductor $$R_H = \frac{-V_H b}{I_X B} \qquad (10)$$

Mobility of charge carriers

We know that hall coefficient $R_H = \frac{-1}{ne}$

This expression is correct only when the charge carriers is free from any attractive force in energy band and moves with constant drift velocity. But this is not true in the case of semiconductors.

Considering the average speed, it is shown that $R_H = \frac{-1.18}{ne}$ for electrons and $R_H = \frac{1.18}{pe}$ for holes.

We know that the electrical conductivity and mobility is related by $\sigma = n\, e\, \mu_e$

(or) $\mu_e = \frac{\sigma}{ne}$ & hence $\mu_e = \frac{\sigma_e}{ne}$ and hence $\mu_e = \frac{-R_H \sigma_e}{1.18}$ (11)

Similarly $\mu_h = \frac{-R_H \sigma_h}{1.18}$ (12)

Experimental Determination of Hall Coefficient:

The experimental setup for the measurement of Hall voltage is shown in figure.

A semiconducting material is taken in the form of a rectangular slab of thickness *'t'* and breadth '*b*'. A suitable current I_x ampere is allowed to pass through this sample along the X axis by connecting it to battery

The sample is placed between the poles pieces of an electromagnet such that the applied magnetic field coincides with the z – axis.

Hall voltage (V_H) which is developed in the sample is measured by fixing two probes at the centers of the bottom and top faces of the sample.

By measuring Hall voltage, Hall coefficient is calculated from the formula $R_H = \frac{-V_H b}{I_X B}$

Applications

(i) The sign of the hall coefficient is used to determine whether a give semiconductor is *n* – type or *p* – type

(ii) Once Hall coefficient R_H is measured, the carrier concentration can be determined from

$n = 1 / e R_H$

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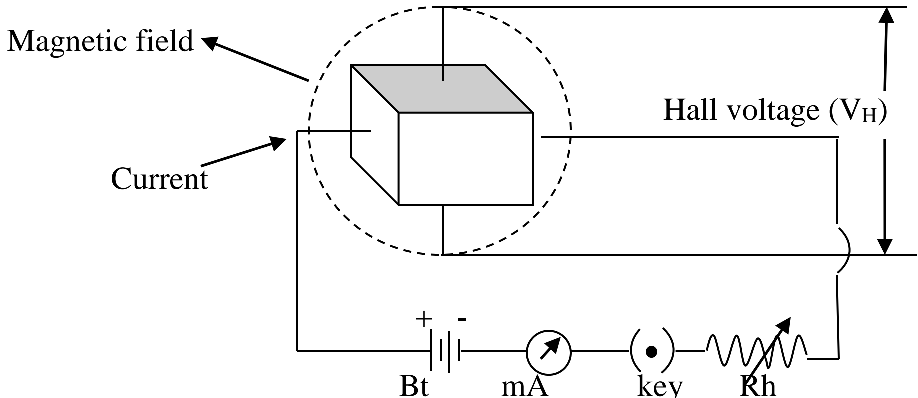
(iii) The mobility of charge carriers can be obtained if conductivity is known. $\mu_e = \sigma_e R_H$

(iv) Hall voltage V_H for a given current is proportional to B. Hence measurement of V_H measures the magnetic field B.

(v) This instrument gives an output proportional to the product of two signals. Thus if current I is made proportional to one input and if B is made proportional to the other input, then the Hall voltage V_H is proportional to the product of the two inputs.



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2. Semiconducting Materials

Part – A

1. Define drift current

The electric current produced due to the motion of charge carriers under the influence of an external electric field is known as drift current

2. Define diffusion current

The non-uniform distribution of charge carriers creates the regions of uneven concentrations in the semiconductor. The charge carriers moving from the region of higher concentration to the regions of lower concentration leading to diffusion current.

3. Differentiate Schottky diode and ohmic contacts?

S.No	Schottky diode	Ohmic contact
1.	It acts as a rectifier	It acts as a resistor
2.	Resistance is low during forward bias an very high during reverse bias	Resistance remains same in both the biasing voltage
3.	Work function $\varphi_m > \varphi_{semi}$	Work function $\varphi_m < \varphi_{semi}$
4.	Formed by the combination of metal and *n* – type semiconductor	Formed by the combination of metal and heavily doped semiconductor

4. Differentiate Schottky diode and *p* –*n* diode

S.No	Schottky diode	*p* –*n* diode
1.	Forward current due to thermionic current	Forward current due to diffusion current
2.	Charge carriers are only due to thermal agitation	Charge carriers are due to impurities and thermal agitation
3.	Reverse current is due to majority charge carrier that overcome the barrier	Reverse current due to minority carriers diffusing to the depletion layer and rifting to the other side
4.	Cut in voltage is ~ 0.3 V	Cut in voltage is ~ 0.7 V
5.	High switching speed	Switching speed is limited

5. What is meant by ohmic contact?

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It is a type of metal semiconductor junction formed by a contact of a metal with heavily doped semiconductor. When the semiconductor has a higher work function than that of metal, then the junction formed is called the Ohmic junction

6. What is Schottky diode?

It is a junction formed between a metal and n type semiconductor. When the metal has a higher work function than that of n – type semiconductor then the junction formed is called Schottky diode.

7. Mention any three hall devices?

Gauss meter, Electronic watt meter an electronic multiplier

8. What are the advantages of Schottky diode?

(i) It has very low capacitance
(ii) It will immediately switch from ON to OFF state
(iii) Small voltage is enough to produce high current
(iv) It has high efficiency
(v) It operates at high frequencies
(vi) It produces less noise

9. What are the uses of ohmic contact?

It is used to connect one semiconductor device to another, an IC, or to connect an IC to its external terminals.

10. What are the applications of Schottky diode?

(1)It is used for rectification of signals of frequencies even exceeding 300 MHz
(2)It is used in switching device at frequencies of 20 GHz
(3)It is used in radio frequency applications
(4)It is widely used in power supplies

Part – B

1. Derive an expression to find the total current density due to drift and difussion of electrons and holes in semiconductor?

The net current flow in semiconuctor is due to drift and diffusion transport.

Drift transport

In the absence of electric field, the random motion of charge carriers will not contribute current because the charge movement in one direction is balance by the charge movement in the other direction. When the external field is applied, the electrons are attracte to the positive terminal and the holes are attracte to the negative terminal. This net movement is termed as drift transport. This transport overcomes the thermal movement and produces current density

Therefore, current density due to electron drift is $J_e = n_e\, e\, v_d$ (1)

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Since $v_d = \mu_e E$ (2)

Substitute (2) in (1), we get

$J_e = n_e \, e \, \mu_e E$ (3)

Similarly, for holes, $J_h = n_h \, e \, \mu_h E$ (4)

Then the total drift current is $j_{dr} = n_e \, e \, \mu_e E + n_h \, e \, \mu_h E$ (5)

We know that $J = \sigma E$ (6)

Therefore $\sigma_{dr} = n_e \, e \, \mu_e + n_h \, e \, \mu_h$ (7)

For an intrinsic semiconductor $n_e = n_h = n_i$

& Hence $\sigma_{dr} = n_i \, e[\, \mu_e + \mu_h \,]$ (8)

Diffusion transport

The non-uniform distribution of charge carriers creates the regions of uneven concentrations in the semiconductor. The charge carriers moving from the region of higher concentration to the regions of lower concentration leading to diffusion current

Hence the concentration of charge carrier (Δn_e) varies with distance x in a semiconductor.

The rate of flow of charge carriers is $\infty \frac{\partial}{\partial x}(\Delta n_e)$

Rate of flow of electrons = $-D_e \frac{\partial}{\partial x}(\Delta n_e)$

Where D_e is the electron diffusion coefficient

Current density due to electrons = charge X rate of flow of electrons

$$\text{i.e.,} \quad J_e = D_e e \frac{\partial}{\partial x}(\Delta n_e)$$

Similarly for holes, $J_h = -D_h e \frac{\partial}{\partial x}(\Delta n_h)$

Thus, if an electric field is applied to the semiconductor, the total current contribution is due to both drift and diffusion transport.

Net current due to both electrons and holes can be obtained as

$$J_{total} = n_e \mu_e e E + e D_e \frac{\partial}{\partial x}(\Delta n_e) + n_h e \mu_h E - D_h e \frac{\partial}{\partial x}(\Delta n_h)$$

2. Explain any three hall devices?

(a) **Gauss meter**

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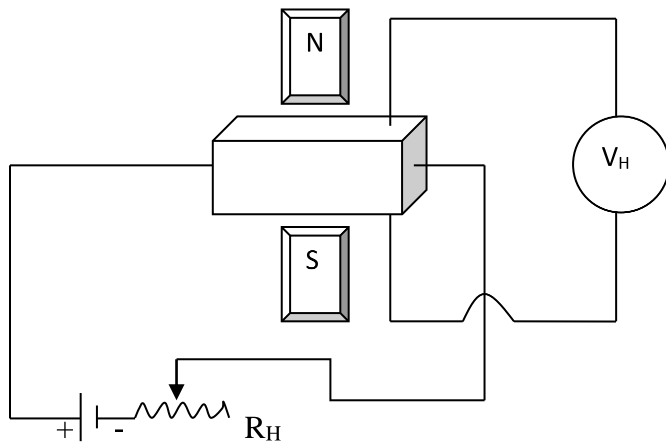
The hall voltage, we have $V_H = \frac{R_H B_Z I_X}{b}$. In this, $V_H \propto B_z$ for a given hall element; R_H an b are constant. The current I through Hall element is also kept constant. This principle is used in Gauss meter. It is used for measuring magnetic field. The variation of Hall voltage with magnetic field is shown in figure. The voltmeter which is used to measure V_H can be directly calibrated in terms of Gauss. The graph can be also used to measure any unknown magnetic fields.



(b) Electronic Multipliers

From Hall effect, we have $V_H = \frac{R_H B_Z I_1}{b}$. Since R_H an b are constant for an element

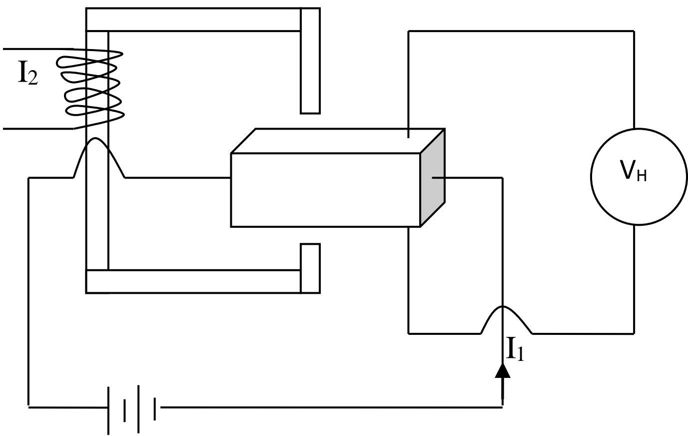
$V_H \propto B_z I_1$

But the magnetic field B_Z is proportional to current (I_2) through the coil.

i.e., $V_H \propto I_2$

$\therefore V_H \propto I_1 I_2$

V_H is a measure of the product of two currents. This is the basic principle used in analog electronic multipliers. The figure shows the circuit diagram for electronic multiplier.



(c) Electronic Wattmeter

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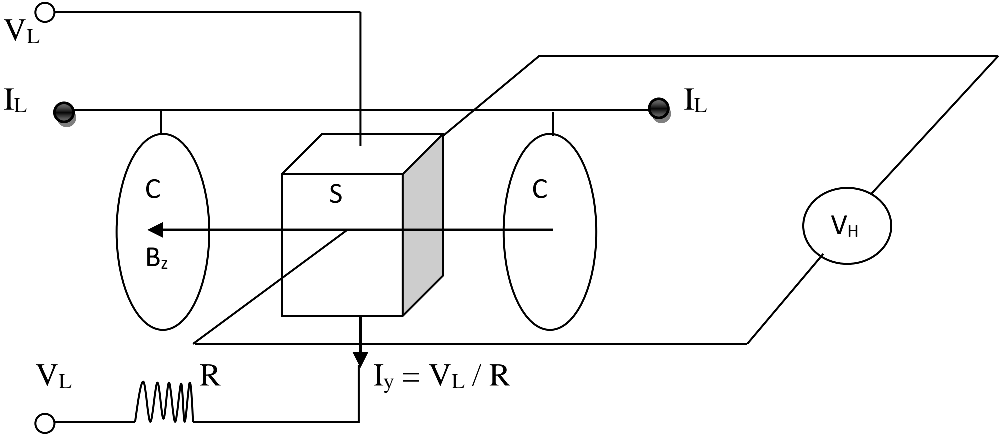
Hall effect is used to measure electrical power dissipate in a load. The instrument used to measure the power in a circuit using Hall effect principle is known as Hall effect – Wattmeter.

S is Hall element sample. It is place in a magnetic field B_z produce by the load current I_L passing through the coils *CC* as shown in figure. The voltage cross the load V_L drives the current $I_y = V_L / R$ through the sample. *R* is a series resistance which is >> than the resistance of the sample and that of the load. Also, $I_y << I_L$. If *b* is the breadth of the sample, then the measured Hall voltage $V_H = \frac{R_H B_Z I_y}{b}$. Since V_H and *b* are constant, $V_H \propto B_z I_y$

Since $B_z \propto I_L$ and $I_y \propto V_L$ & hence $V_H \propto I_L V_L$

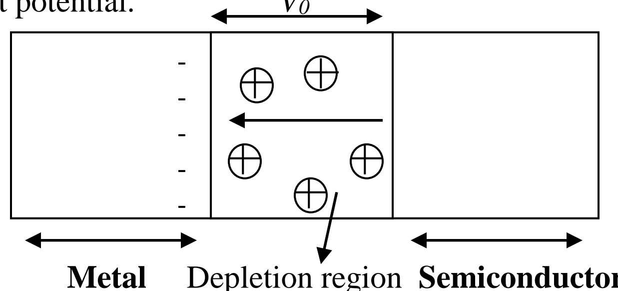
This is the electric power dissipated by the load. The voltmeter that measures V_H can be calibrate to read power directly.



3. Describe the construction and working of Schottky diode? What are its advantages?

It is the junction formed between a metal and n – type semiconductor. When the metal has a higher work function than that of n – type semiconductor then the junction forme is called Schottky diode. The fermi level of the semiconductor is higher (since its work function is lower) than the metal. Figure shows Schottky diode and its circuit symbol.

The electrons in the conduction level of the semiconductor move to the empty energy states above the fermi level of the metal. This leaves a positive charge on the semiconductor side and a negative charge (due to the excess electrons) on the metal sie as shown in figure. This leads to a contact potential.



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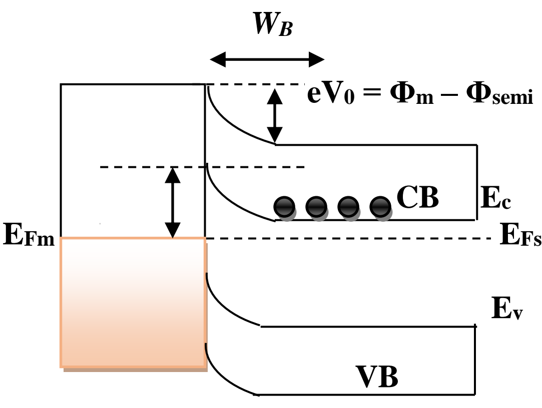
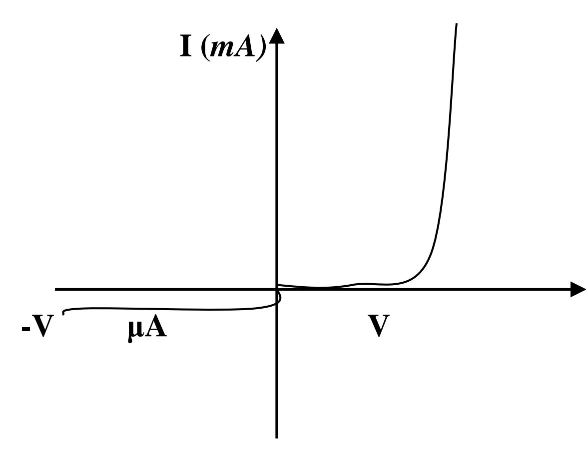
Energy band diagram





When a Schottky junction is formed between metal and semiconductor, fermi level lines up. Also a positive potential is formed on the semiconductor side. The formation of a depletion region of width W_D within the semiconductor is shown in figure. Because the depletion region extends within a certain depth in the semiconductor, there is bending of the energy bands on the semiconductor side. *Band* bend up in the direction of the electric field produced in depletion region. There is a built in potential V_o in the Schottky junction. From the figure this is given by the difference in work functions $eV_0 = \varphi_m - \varphi_{semi}$

Working

The behaviour of Schottky diode is further studied by forward and reverse bias.

(a)Forward Bias

In this bias, metal is connected to positive terminal and $n-type$ semiconductor is connected to negative terminal of the battery. In the forward biased Schottky junction, the external potential opposes the in- built potential. The electrons injected from the external circuit into the $n - type$ semiconductor have a lower barrier to overcome before reaching the metal. This leads to a current in the circuit which increases with increasing external potential.

(b) Reverse Bias

In reverse bias, metal is connected to negative terminal and $n - type$ semiconductor to positive terminal of the battery. In the case of reverse bias, the external potential is applied in the same direction as the junction potential. This increases the width of depletion region further and hence there is no flow of electron from semiconductor to metal. So Schottky junction acts as rectifier. i.e., it conducts in forward bias but not in reverse bias.

$V-I$ Characteristics

The $V-I$ characteristics of the junction is shown in figure. There is an exponential increase in current in the forward bias while there is a very small current in reverse bias.

Advantages

It has very low capacitance
It will immediately switch from ON to OFF state (fast recovery time)

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Applying a small voltage is enough to produce large current
It has high efficiency
It operates at high frequencies
It produces less noise.

4. Write a note on ohmic contact?

An ohmic contact is a type of metal semiconductor junction. It is formed by a contact of a metal with a heavily doped semiconductor. When the semiconductor has a higher work function than that of metal, then the junction formed is called the ohmic junction.

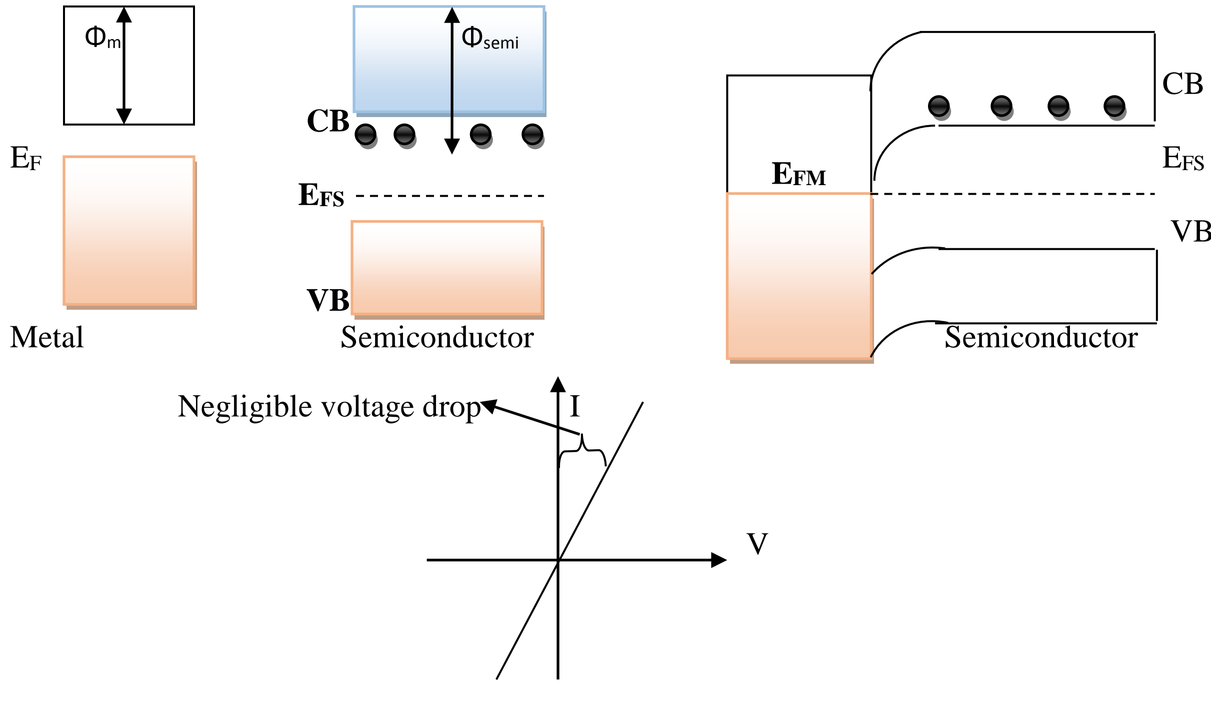
Here, the current is conducted equally in both directions and there is a very little voltage drop across the junction. Before contact, fermi levels of the metal and semiconductor are at different positions as shown in figure.

Working

After contact, the ohmic junction is shown in figure. At equilibrium, the electrons move from the metal to the empty states in the conduction band of semiconductor. Thus, there is an accumulation region near the interface (on the semiconductor side). The accumulation region has higher conductivity than the bulk semiconductor due to this higher concentration of electrons. Thus, a ohmic contact behaves as a resistor conducting in both forward and reverse bias. The resistivity is determined by the bulk resistivity of the semiconductor.

***V – I* Characteristics**

The *V-I* characteristics of the ohmic contact is shown in figure. The current is directly proportional to the potential across the junction and it is symmetric about the origin, as shown in figure. Thus, ohmic contacts are non-rectifying and show negligible voltage drop and resistance irrespective of the direction and magnitude of current.



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Applications

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

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3. Magnetic Properties of Materials

Part – A

MAGNETIC MATERIALS

1. **What is Bohr magnetron?**
When the atom is placed in a magnetic field, the orbital magnetic moment of the electron is quantized. A quantum of magnetic moment of an atomic system is known as Bohr magnetron.

$$\mu_B = \frac{eh}{4\pi m}$$

2. **What is Curie constant & Curie law?**

Paramagnetic susceptibility $\chi = \frac{N\mu_0 \mu_m^2}{3kT}$ (or) $\chi = \frac{C}{T}$ where N is the number of atoms per unit volume; μ_0 is the permeability of free space; μ_m – Induced dipole moment

Thus "*susceptibility of a paramagnetic substance varies inversely with the tempecture"* is called Curie law and *C* is the curie constant.

3. **What is Curie – Weiss law?**
Ferromagnetic materials exhibit spontaneous magnetization below a tempecture called the curie tempecture and above it becomes paramagnetic and obeys Curie Weiss law given by
Susceptibility $\chi = \frac{C}{T-\theta}$. Where *C* – Curie constant & θ – paramagnetic curie tempecture.

4. **What is domain theory of ferromagnetism?**
According to Weiss, *a ferromagnetic specimen consists of large number of small regions called domains which are spontaneously magnetized due to the parallel alignment of all magnetic diploes. The direction of spontaneous magnetization varies from domain to domain.*

5. **What are energies involved in origin of domains in ferromagnetic material?**
Magnetostatic energy, Crystalline (or) anisotropic energy, Domain wall energy, Magnetostriction energy.

6. **On the basis of magnetic moments how the materials are classified as Dia, Para, Ferro, Antiferro & ferri magnetic?**
(i) Materials which does posses any permanent dipole moment are known as diamagnetic materials
(ii) If the permanent dipole do not interact among themselves and are align in random direction, then those materials are paramagnetic.
(iii) If the permanent dipole are strong and align themselves in parallel, then those materials are called diamagnetic.
(iv) If the permanent dipole are strong and align themselves antiparallel with equal magnitude, then those materials are called Antiferromagnetic
(v) If the permanent dipole are strong and align themselves antiparallel with unequal magnitude, then those materials are called Ferrimagneic

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7. **Give the properties of Diamagnetic materials?**
   (i) Permanent dipoles are absent. Therefore the magnetic effects are very small
   (ii) When placed inside the magnetic field, magnetic lines of forces are repelled
   (iii) The magnetic material have negative susceptibility
   (iv) Magnetic susceptibility is independent of applied field strength and tempecture
   (v) Relative permeability is slightly less than unity
   (vi) Example: Gold, Bismuth and Organic materials
8. **Give the properties of Paramagnetic Materials?**
   (i) It posses permanent magnetic dipoles
   (ii) When placed inside the magnetic field, it attracts the magnetic lines are forces
   (iii) In the absence of the magnetic field, the dipoles are randomly oriented. There is a small amount of magnetic moment in the absence of external field.
   (iv) When magnetic field is applied, magnetic moment along the field direction increases with increasing magnetic induction.
   (v) Paramagnetic susceptibility is positive and greatly depends on tempecture.
   (vi) Paramagnetic susceptibility is independent of applied field strength.
   (vii) When the tempecture is less than Curie tempecture it becomes diamagnetic.
9. **What are the properties of Ferro magnetic materials?**
   (i) It exhibits magnetization even in the absence of external field
   (ii) This materials exists as ferro magnetic when tempecture is below ferromagnetic curie tempecture and become paramagnetic above ferromagnetic curie tempecture
   (iii) It consists of number of small spontaneously magnetized region called domains
   (iv) During heating they loss their magnetization slowly
   (v) Spin alignment are parallel in same direction
   (vi) They attracts magnetic lines of forces strongly
   (vii) Susceptibility is very large & positive
10. **What are the properties of ferri magnetic materials?**
   (i) It posses net magnetic moment
   (ii) Magnetic susceptibility is very large & positive. It is given by $\chi = \frac{C}{T \pm \theta_N}$
   Where θ_N- Neel Tempecture.
   (iii) Spin alignment is antiparallel of different magnitude
   (iv) The susceptibility is graphically tempecture dependent.
11. **What are the essential differences between hard and soft magnetic materials?**

S.No	Hard magnetic materials	Soft Magnetic Materials
1.	They have large hysteresis loss	They have small hysteresis loss
2.	The eddy current loss is high	Eddy current loss is low
3.	They have small values of permeability & Susceptibility	They have large values of permeability & Susceptibility
4.	Domain wall movement is difficult& irreversible in nature	Domain wall moves easily& reversibly
5.	The coercivity & retentivity are large	The coercivity & retentivity are small

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6.	Eg: Carbon steel, Tungsten Steel, Chromium Steel.	Eg: Iron, Ferrites, Silicon Alloys

12. Define Susceptibility?

The ratio of the intensity of magnetization produced in the sample (I) to the magnetic field intensity which produces the magnetization (H). i.e., $\chi = \frac{I}{H}$

13. What is antiferromagnetism?

Electron spin of neighbouring atoms are align antiparallel, their susceptibility is small and positive, and they greatly depends on tempecture.

14. What are Ferrites and mention its types?

Ferrites are modified structure of iron with no carbon atoms in which the adjacent magnetic moment are of unequal magnitudes aligned in antiparallel direction.

General Formula: $X^{2+} Fe^{3+} O_4^{2-}$

Types: Regular Spinal, Inverse Spinal

15. **State the applications of ferrites?**

(i) They are used in transformer cores for high frequencies up to microwaves.

(ii) They are used in radio receivers to increase the sensitivity and selectivity of the receiver

(iii) They are used in digital computers and data processing circuits

(iv) They are used in power limiting and harmonic generation devices

16. What is ferrite core memory?

It is the memory made up of a ferrite core in the form of rings used for random storage of data ‘0’ & ‘1’ by magnetizing the ring in any of the two opposite direction.

17. **What do you understand from bubble storage?**

It is the direct access storage medium made up of a soft magnetic materials with magnetic domains of few ‘μm’ in diameter. These magnetic bubbles are the electronic analogue of the magnetic disc memories used in computers.

18. **Define Hysteresis?**

When the ferromagnetic material undergo a cycle of magnetization, the intensity of magnetization (I) & magnetic flux density (B) lags behind the applied magnetic field strength (H) & this process is called Hysteresis.

19. What is the principle of magnetic recording system?

It states the data in the form of magnetization pattern as a sequence of binary magnetization states in the magnetic medium because the ferromagnetic material produces the magnetic dipoles align themselves parallel to each other.

20. What are the advantages and disadvantages of magnetic discs?

Advantage:

(i) It has very large storage capacity

(ii) Thousands of files can be permanently stored

(iii) Very high speed in writing & reading the information

(iv) Prevented from dust particles, because it is sealed

Disadvantage:

(i) It is very costly

(ii) If data is once corrupted, there is a heavy loss of data

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Part – B

1. How the hysteresis curve is explained on the basis of the domain theory?

When a Ferromagnetic is subjected to external field, there is an increase in the value of the resultant magnetic moment due to

(i) The movement of domain walls

(ii) The rotation of domains

When a weak external field is applied, the domain walls are displaced slightly in the soft direction of magnetization. This gives rise to small magnetization corresponding to the initial portion of the hysteresis curve (OA) as shown in figure .Now, if applied field is removed, then the domains return to its original state and it is known as "**Reversible Domains**".

When a strong external field is applied, large number of domains contributes to the magnetization and thus the magnetization increases rapidly with "H"↑

Here, even when the field is removed, because of the displacement of domain wall to a very large distance. The domain boundaries do not come back to their original position. This process is indicated as (AB) in Figure and this domains are called **"Irreversible Domains".**

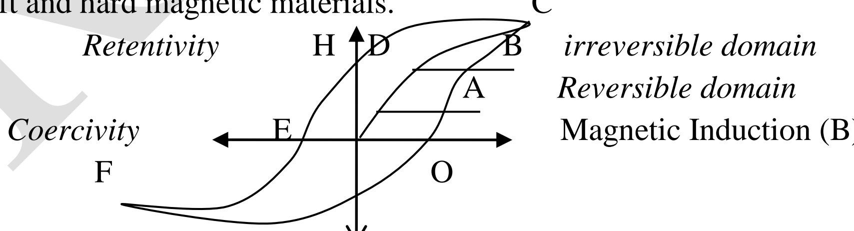
At point "B" all the domains have got magnetized along the soft direction. Now, when the field is further increased, the domains start rotating along with the field direction and the anisotropic energy is stored in the "*Hard Direction*" represented as "BC" in figure

Thus the specimen is said to attain the maximum magnetization. At this position, even after the removal of external field the material possess maximum magnetization called **"Retentivity"** represented by "OD" in figure

Actually after the removal of the external field, the specimen will try to attain the original configuration by the movement of Bloch wall. But this movement is stopped due to the presence of impurities, lattice imperfections, etc., therefore to overcome this, a large amount of reverse magnetic field is applied to the specimen. The amount of energy spend to reduce the magnetization of Zero is called **"Coercivity"** represented by "OE" in figure

Hysteresis Loss:

It is the loss of energy in taking a ferromagnetic specimen through a complete cycle of magnetization and the area enclosed is called "Hysteresis Loop". Based on this area of hysteresis, the magnetic are classified as soft and hard magnetic materials.



2. Describe the structure of ferrites? How the magnetic moment of ferrite molecule is calculated?

Substance which possess a spontaneous magnetization in which the magnetic moments of the two sub lattice are opposite in direction but not exactly equal in magnitude are called "Ferrites".

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Ferrites are compounds of iron oxides with oxides of other metals

General Formula: $X^{2+} Fe_2^{3+} O_4^{2-}$

Where $X^{2+} \rightarrow Mg^{2+}, Zn^{2+}, Fe^{2+}, Mn^{2+}, Ni^{2+}$, etc.,

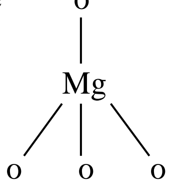
Examples: If X^{2+} is Ni^{2+} then $Ni^{2+} Fe_2^{3+} O_4^{2-}$ is a nickel ferrite.

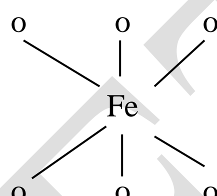
X^{2+} is Fe^{2+} then $Fe^{2+} Fe_2^{3+} O_4^{2-}$ is a ferrous ferrite.

Ferrites formed usually have a face centered cubic structure of oxygen ions closely packed together with the divalent and trivalent metal ions in the interstitial sites. This structure is called spinal structure. There are two types of ferrites.

(i) Regular spinal ferrite structure

(ii) Inverse spinal ferrite structure





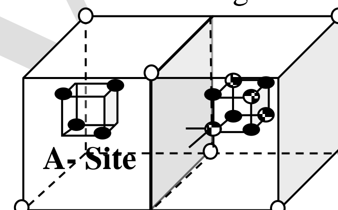
(i) Regular spinal ferrite structure:

In this type each divalent metal ion is surrounded by four O^{2-} Ions in the tetrahedral fashion. It is called "A" site. Totally in a unit cell, there will be 8 tetrahedral sites (8A)

Each trivalent metal ion is surrounded by six O^{2-} Ions in the octahedral fashion. It is called "B" site. Totally in a unit cell, there will be 16 octahedral sites (16B)

Example: $Mg^{2+} Fe^{3+} O_4^{2-}$

Thus in the regular spinal, each divalent metal ion (Mg^{2+}) exists in a tetrahedral form (A site) and each trivalent metal ion (Fe^{3+}) exists in an octahedral from (B site). Hence the sites "A" and "B" combine together to form a regular spinal ferrite structure as shown in figure.



○ Divalent metal ion

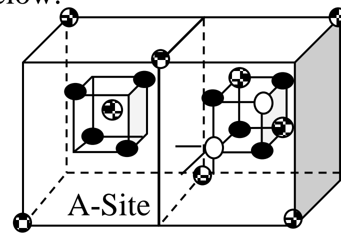
Trivalent metal ion

● Oxygen ion

(ii) Inverse spinal ferrite structure

Example: $Fe^{3+} [Fe^{2+} Fe^{3+}] O_4^{2-}$

In this, the trivalent metal ions (Fe^{3+}) occupies all the A sites (tetrahedral) and half of the B sites (octahedral) also. Thus the left out B sites will be occupied by the divalent (Fe^{2+}) metal ions. The inverse spinal ferrite structure is shown in figure below.



Types of interaction present in ferrites:

According to Neel, there are three types of interaction, AA, BB and AB. Out of which AA and BB are negative and considerably weak than AB interaction. Thus the effect of AB interaction dominates and gives rise to antiparallel spin arrangement.

Magnetic Moment of a ferrite molecule:

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The orbital and spin magnetic moment of an electron in an atom can be expressed in terms of Bohr magnetron $\mu_B = \left(\frac{eh}{4\pi m}\right)$, saturation magnetization of a ferrite molecule can be calculated from number of unpaired spins of Fe^{2+} and Fe^{3+}

Consider Fe^{3+} [Fe^{2+} Fe^{3+}] O_4^{2-}

(i) Fe^{2+} ions have 6 electrons in 3d shell. Out of '6', 2 electrons are paired and 4 electrons are unpaired. Therefore, Fe^{2+} gives 4 Bohr Magnetron.

↑↑↑↑↑
↓↓↓↓↓ ↑↑↑↑

(ii) Fe^{3+} ions have 5 electrons are unpaired

Therefore, $Fe3^{+}$ gives 5 Bohr Magnetron

Since we have two Fe^{3+}, totally the Fe^{3+} gives 2x5=10 Bohr magnetron.

Total magnetization = 4+10=14 Bohr Magnetron. But total magnetic moment got only 4.08 MB. Because, in ferrites half of the magnetic spins of Fe_2^{3+} ions are parallel in one direction and the remaining half of Fe_2^{3+} ions are parallel in opposite direction and hence they cancel each other and exists 4 Bohr magnetron which is nearly equal to 4.08 MB.

3. Classify the magnetic materials on the basis of their spin? (or) Explain the origin of magnetic moments?

The magnetic moment originates from the orbit motion and spinning motion of electrons in an atom. In general, there are three contributions to the angular momentum of an atom.

(i) Orbital angular momentum of the electrons:- $\mu_\circ$

Consider an electron revolving in an orbit with radius 'r' moving with linear velocity 'v' and produces a constant angular velocity 'w'. Any electron revolving around orbit produces magnetic field perpendicular to its plane which produces an orbital magnetic moment given by

$$\mu_0 = IA$$

$$= \left(\frac{ew}{2\pi}\right)\pi r^2$$

But v = rω and $\omega = \frac{v}{r}$

$$\therefore \mu_0 = \left(\frac{evr}{2}\right)$$

$$= -e\left(\frac{mvr}{2m}\right) \qquad \mu_\circ = \left(\frac{-el}{2m}\right)$$

By quantum theory, this orbital magnetic moment of an atom can be expressed in Bohr magnetron given by $\mu_B = 9.27 \times 10^{-24}$ Am^2

(ii) Electron spin magnetic moment (μ_S)

In an atom, every two electrons will form a pair with opposite spins. Thus the resultant spin magnetic moment is zero. But in magnetic materials, the unpaired electrons spin magnetic moments interacts with the

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adjacent atom's to form unpaired electron spin magnetic moment which is responsible for ferro and paramagnetic behaviour of materials. Accordingly to Quantum theory, spin magnetic moment $\mu_S = \frac{e}{2m} S$

Where $\mu_S = \pm 1$ Bohr Magnetron.

(iii) Nuclear spin magnetic moment (μ_N)

The mass of the nucleus is larger than that of electron by a factor of the order of 10^3. Hence, nuclear spin magnetic moment is of the order of 10^{-3} Bohr magnetron.

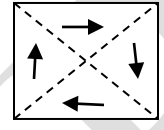
Since μ_S and μ_N are very small, then the practical purpose, the total magnetic moment arises due to spin magnetic moment.

4. (a) Explain the formation of domain structure in a Ferro magnetic material?
(b) Write a short note on (i) Exchange energy (ii) Anisotropy energy (iii) Bloch wall energy and (iv)Magnetostrictive energy? (or) what are the energies involved in domain growth? (or) explain the origin of Domain theory of ferromagnetism?

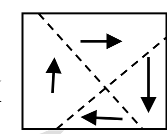
According to Weiss, *Ferro magnetic materials consists of large number of small regions called domain. Each domain varies from 10^{-6} to entire size of the crystal.* In each domain the spontaneous magnetization is due to parallel alignment of all magnetic domains. The direction of spontaneous magnetization varies from domain to domain. Hence the resultant magnetization may be zero or nearly zero, when the external field is applied. There are two ways of alignment of a random domain:

(i) By the motion of domain walls:-
The volume of the domains that are favorably oriented with respect to the magnetizing field increases at the cost of those that are unfavorably oriented as shown in figure

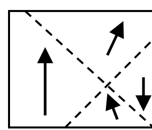
(ii) By the rotation of domains:-
When the applied magnetic field is strong, rotation of the direction of magnetization occurs in the direction of the field as shown in figure



Weak Field H



Strong Field H



H = 0

By bitter powder pattern, when a drop of colloidal suspension of finely divided ferromagnetic material has strong magnetic field near boundaries when external magnetic field is applied domain walls are move. The domain walls & their movements can be observed from microscope.

In the process of domain growth, four types of energies are involved:

(i) Exchange energy (or) Magnetic field energy (or) Magneto-static energy:-

"The interaction energy makes the adjacent dipoles align themselves. It arises from the interaction of electron spins".

This exchange energy is the energy required in assembling the atomic magnets in single domain and this work done is stored as potential energy, the size of domain may be obtained from the principal of minimum energy volume of domain = 15^2 to 10^{-6} cm^3.

(ii) Anisotropy energy:-

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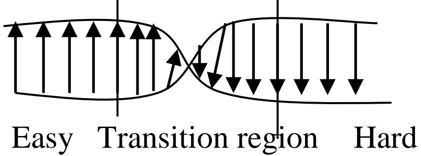
In ferromagnetic crystals, energy of magnetization is found to be a function of crystals orientation i.e., crystal have easy and hard direction of magnetization.
Example: In BCC iron, easy direction is [100], the medium direction is [110] and the hard direction is [111].
"The excess energy required to magnetize a specimen in a particular direction over that required to magnetize it along the easy direction" is called crystalline anisotropy energy.

(iii) Domain wall energy (or) Bloch wall energy:-

The thin region that separates adjacent domains magnetized in different direction is called "Domain wall energy". Bloch walls are 200 to 300 lattice constant thicknesses. It changes the spin when transfer from one domain to other. The exchange energy is lower when the change is gradual but the anisotropy energy is less when spin change abruptly. Hence the Bloch wall compromise between two.



Easy Transition region Hard

(iv) Magnetostrictive energy:-

When the domains are magnetized in different directions, they will either expand (or) shrink. Therefore there exists a deformation (i.e., change in dimension of a material) when it is magnetized this phenomenon is known as Magnetostriction and the energy produced is Magnetostrictive energy.

5. Distinguish briefly about diamagnetic material, paramagnetic material and ferromagnetic material?

S.No		Diamagnetic material	Paramagnetic material	Ferromagnetic material
1.	Definition	The material with no permanent dipole moment. The external field decreases the magnetic induction present in the specimen	The material with permanent dipole moment but do not interact among themselves. The external magnetic field increases the magnetic induction present in the specimen	The material with strong permanent dipole moment and interact among themselves. The external field increases a large magnetic induction in the specimen.
2.	Susceptibility and its temperature dependence	It is negative and independent of temperature and applied magnetic field.	It is always positive and small and it is inversely proportional to absolute temperature of material	It is always positive and large and depends on temperature in complex manners.

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3.	Behaviour of material in magnetic field	The magnetic lines of forces are repelled away from the material. Bout > Bin	The magnetic lines of forces are attracted towards the centre of material. Bin > Bout	The magnetic lines of forces are highly attracted towards the centre of material. Bin >> Bout
4.	Spin on magnetic moment alignment	No spin (or) magnetic moment	All spins (or) magnetic moments are randomly oriented	All spins (or) magnetic moments are orderly oriented.
5	Origin	Arises from lamer precession	Arises from the magnetic moments orientation	Arises from spontaneous magnetization due to total molecular magnetic field.
6.	Magnetic phase transition	At low temperature, super conductor are diamagnetic when temperature increases it becomes conductor.	When temperature is less than curie temperature. It is diamagnetic. But paramagnetic curie temperature is low.	When temperature is higher than curie temperature it is paramagnetic. But in ferromagnetic curie temperature is high.
7.	Examples	Hydrogen, Bismuth	Aluminum, Platinum	Iron, Nickel and Cobalt.

6. What are hard magnetic materials and soft magnetic material? Give its properties?

Hard magnetic materials:-

The materials which are very difficult to magnetize and demagnetize called hard magnetic materials.

Soft magnetic materials:-

The materials which can be easily magnetized and demagnetized are called soft magnetic materials.

S.No	Soft Magnetic Materials	Hard Magnetic Materials
1.	They can be easily magnetized and demagnetized.	They cannot be easily magnetized or demagnetized.
2.	The hysteresis loop is narrow	The hysteresis loop is broad

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3.	The hysteresis loss is minimum	The hysteresis loss is maximum
4.	Susceptibility and permeability are high	Susceptibility and permeability are low
5.	Retentivity and coercivity are small	Retentivity and coercivity are large
6.	They have low eddy current loss	They have high eddy current loss
7.	These materials are free from irregularities like strain and impurities.	These materials have large amount of impurities and lattice defects
8.	It is used to make temporary magnets	It is used to produce permanent magnets
9.	Eg: Iron, Silicon, Alloys, Ferrites	Eg: Carbon steel Tungsten steel, chromium steel.

7. In detail Explain how data are stored in magnetic materials? What are functions of reading & writing Heads? How they are designed?

Magnetic recording involves the storage of data in the form of magnetization pattern as a sequence of binary magnetization states in the magnetic medium.

Reading Process:

An audio tape is simply a polymer packing tape coating with magnetic oxide. The audio signal to be recorded is converted in to current signal & it is passed through electromagnet made up of ferrite which has small air gap of about 0.3m wide. Whenever the current signal passes through the electromagnet, it produces a magnetic field in the material which produces a magnetic field in the recording head (air gap)

When the tape touches the head, the magnetic field present in the head magnetize the magnetic material present in the tape. The recording on the tape is done by fringing magnetic field around the air gap region. This fringing magnetic field magnetizes the audio tape passing under the head at constant speed. Th intensity of the fringing magnetic field varies with the intensity of the current signal. Thus the electrical signal is stored by means of spatial magnetic pattern on the tape. This type of magnetic recording is called *longitudinal recording*

Writing Process:-

The reading process is based on the principle of Faraday's law of electromagnetic induction. A portion of magnetic field present in the tape penetrates through the recording head.

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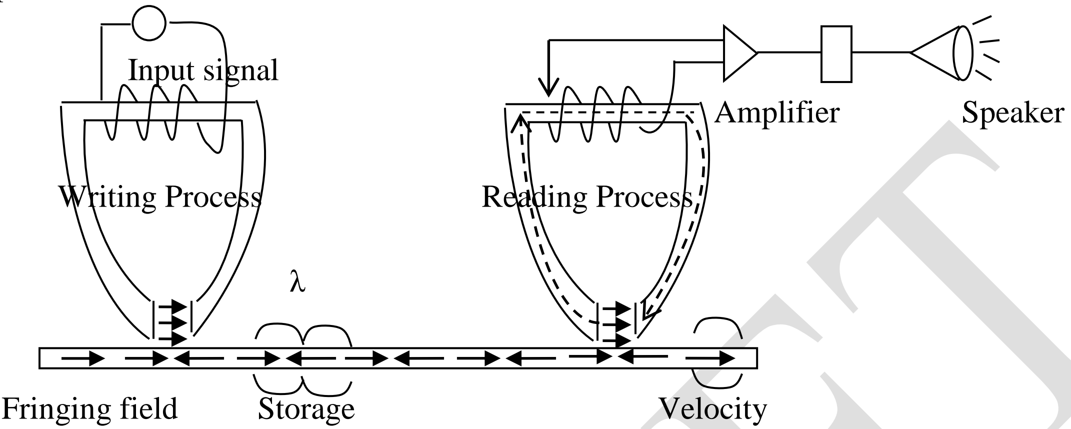
This magnetic field loops around the core of the head. As the tape is moving with a constant velocity, the magnetic field present in the tape while flowing through the core gets converted in to the corresponding voltage signal & the voltage signal is converted into an audio signal by a amplifier & loud speaker.



8. Explain in detail on different magnetic storage data. What are their relative merits & demerits?

In general memory units are the devices used to store the information in the form of bits. [8 bit =1 byte]
The memory units are classified as

(i) Main memory (or) Internal memory
(ii) Auxiliary memory (or) External memory

Main Memory:

The memory unit of CPU is called main memory. Thus data's are write and finally be erased if necessary.
Eg: EPROM, ROM, RAM etc.,

Auxiliary Memory:

This type of memory is also referred to as back-up storages because; it is used to store large volume of data on permanent basis. This date can be accessed or recopied if necessary.
Eg: Magnetic tapes, Magnetic disk, Ferrite core memories and Bubble memories.

1. Magnetic Tape:

The tape is a plastic ribbon with metal oxide material coated on one side which can be magnetized, in this information can be written and also can be read by write/read heads.
Information recorded in the tape is in the form of tiny magnetized and non-magnetized spots on the metal oxide coating. The magnetized spot represents '1' sun magnetized spot represent '0' in binary code. The information can be accessed, processed, erased and can be stored again in same area.

Advantages:-

(i) Storage capacity is large
(ii) Easy to handle
(iii) Loss expensive
(iv) Erased and reused.

Disadvantages:-

(i) It consumes lot of time.

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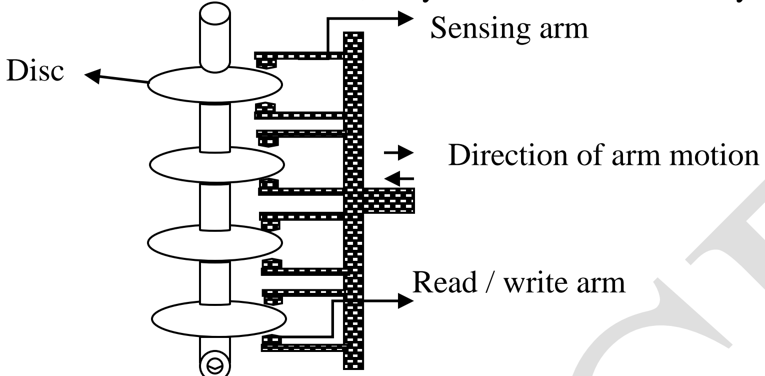
2. Magnetic Disc Devices:

(A) Hard disk drives:

It is the direct access storage device made up of hard aluminum platters. This platter surface is carefully machined for flat. This surface is coated with magnetic oxides and built in to a bar.

Similar such disks are mounted on a vertical shaft, forming a disk pack as shown in figure. The drive mechanism drives the disc pack with the spindle. The data is written can read by the R/W heads in the horizontal sensing arms by moving in and out between the platters with the precaution that the R/W head doesn't touches the surface instead, it fly over the disk surface by a fraction of a mm.



Advantages:-

(i) It has large storage capacity.
(ii) Thousand of files can be permanently stored.
(iii) Very high speed in reading and writing the information
(iv) This is prevented from dust, since they are sealed.

Disadvantages:-

(i) It is very costly
(ii) If data is completed, there is a heavy loss.

(B) Floppy disc drives:

Floppy is made of a very thin and flexible plastic materials coated with magnetic materials. This disc is inserted in floppy disc drive for read/write operation by the read/write head in the disc. Size: 5.25" called mini floppy, 3.25" called micro floppy.

Organization:-

Surface of the floppy disc is divided into a number of concentric circles known as tracks where the information is recorded. The tiny magnetic spots are used to record the logic 1 (or) 0 state. The spot magnetized in one direction are '1' state and in other direction are called '0' state. Each track has number of sectors

Operation;-

When the floppy is put in drive unit. When drive is operated. The floppy disc is rotated which makes physical contact with read/write head. This magnetic material movement is controlled by serve mechanism.

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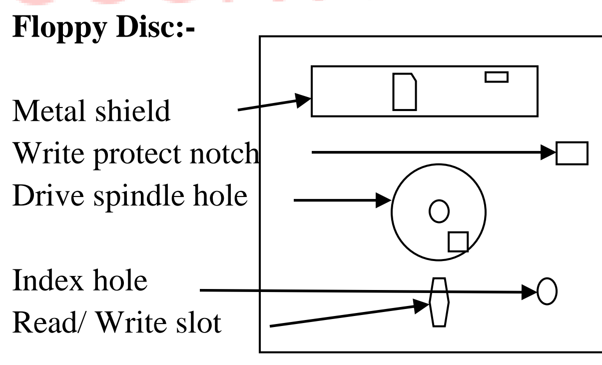
Floppy Disc:-



Advantages:-

(i) Storing and transporting of data is easier.
(ii) Cost is less
(iii) It can reused many times

Disadvantages:-

(i) Storage capacity is less
(ii) Care to be taken for handling.

3. Ferrite Core Memory:

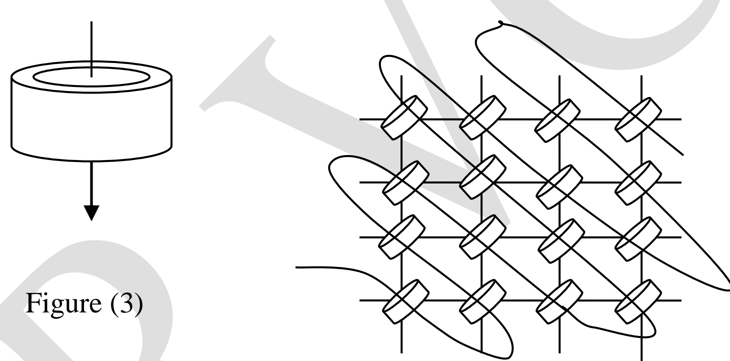


Figure (3)

Here the magnetic core consists of a ferrite core in the shape of a torrid ring as shown in figure.
We know that the ferrites have square hysteresis loop and low coercivity as shown in figure. Such hysteresis is used for making core memory as a different form of magnetic recording.
The magnetic cones of the memory are arranged in a matrix interlaced thought fine metal wires both horizontally and vertically as shown in figure (3)
A change in the state only occurs during reinforced magnetization i.e. both the horizontal current and vertical current pass through the core in same direction. The current passing through one of the wires will not induce a change in the magnetization of the cores reading of the magnetic cores is achieved using a third sense wire threaded through the core. It will pick up an induced voltage, if the core changes state. To facilitate a fast response for a high speed memory, soft magnets are always used in the core.

4. Magnetic Bubbles Memories:

Magnetic bubbles are soft magnetic materials with magnetic domains of a few micrometers in diameter.

Construction:-

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Bubble memory consists of magnetic garnets deposited on a non-magnetic substrate made up of Gadolinium Gallium Garnet (GGG)

When a magnetic field is applied by placing in between two permanent magnets, the magnetic domains contracts and finally forms a small cylindrical domain area which is called magnetic bubble.

These bubbles constitute a magnetic region of one polarity surrounded by magnetic region of opposite polarity.

The information is represented as the presence (or) absence of a bubble at specified location. The bubble position remains unchanged even in the absence of electric power. These bubbles can be moved electronically through the access lines at very high speed and hence its access and storage time is less.

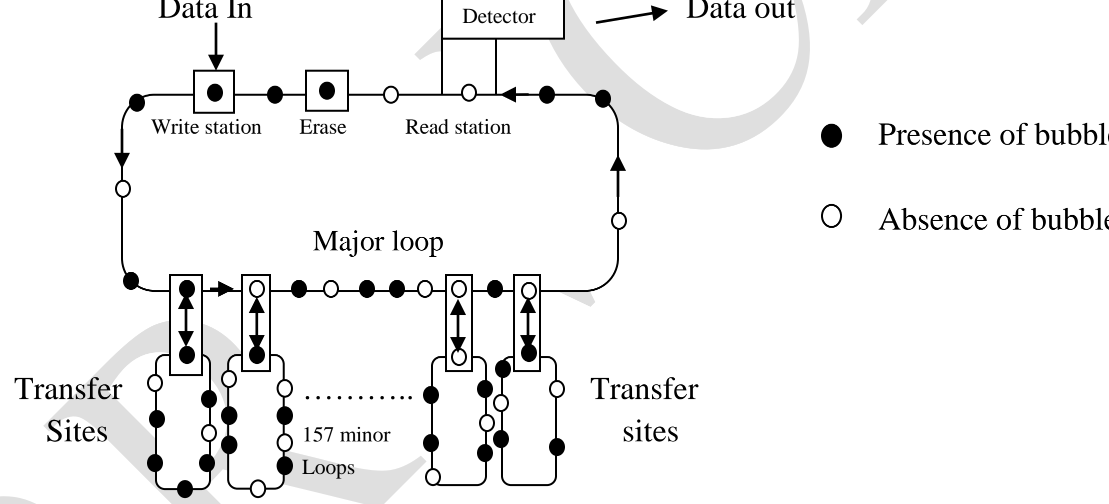
Here presence of bubble is logic ‘1’ state and absence is logic ‘0’ state. The schematic diagram show in fig. It consists of ‘1’ major loop and ‘15’ minor loops which are arranged from right to left. Each minor loops has 641 bubble sites, thousands of coded characters may be stored in a single chip.

Writing Operation:-

When a data has to be stored, the bubbles from the minor loops are transferred to major loop and it goes to write station. In write station the message is entered and the bubble site again comes to minor loop.

Reading Operation:-

To read the data from the storage, the bubble from minor loops are transferred to major loops and it goes to read station, then it comes to minor loop. The data can be altered by the erase station, if we need to erase it.



Advantages:-

(i) Large amount of data stored permanently
(ii) Data is not lost while power is off
(iii) It is a non-volatile memory
(iv) Bubble sites are moved electronically

Disadvantages:-

(i) It requires a high recording time for storing and retrieving the data.

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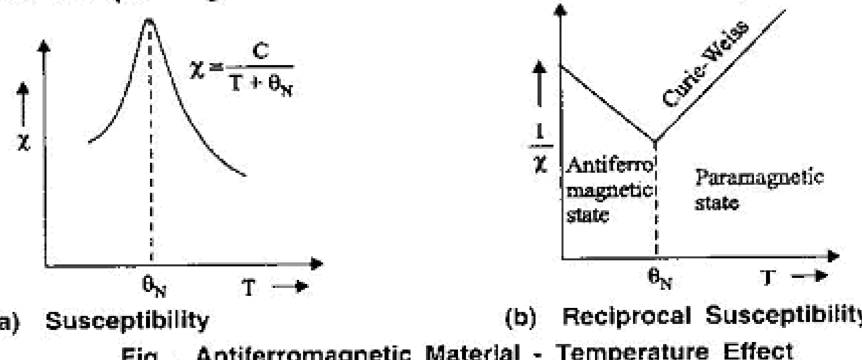
Antiferromagnetic Materials

1. Antiferromagnetic Materials

Any materials having the magnetic interaction between any two dipoles align themselves antiparallel to each other are called antiferromagnetic materials.

Antiferromagnetic materials are crystalline materials, which exhibit a small positive susceptibility in the order of 10^{-3} to 10^{-5}. Electron spin of neighbouring atoms are aligned anti-parallel. The susceptibility increases with increasing temperature and reaches a maximum at a ceratin temperature called Neel temperature, θ_N. With a further increase in temperature, the material goes into paramagnetic state. The material is antiferromagnetic below θ_N.



(a) Susceptibility (b) Reciprocal Susceptibility

Fig. . Antiferromagnetic Material - Temperature Effect

In the paramagnetic state, the variation of inverse susceptibility $\left(\frac{1}{\chi}\right)$ with temperature is linear as shown in Fig. (b). The variation of susceptibility with temperature obeys modified Curie Weiss law.

The susceptibility

$$\chi = \frac{C}{T + \theta_N} \qquad T > \theta_N$$

where, θ_N is called Curie temperature.

C is called Curie constant.

The opposite alignment of adjacent site spin magnetic moments in these materials is produced by an unfavourable exchange interaction.

Examples Manganese oxide (MnO) and Chromium oxide (Cr_2O_3).

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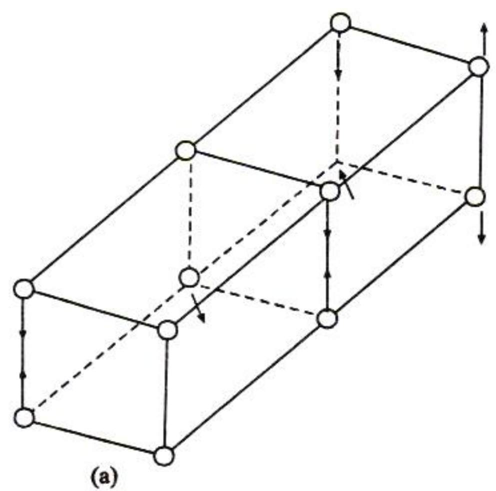
2. Structure

The elements like Manganese and Chromium exhibit antiferromagnetism at room temperature. Antiferromagnetic materials are of little practical interest.



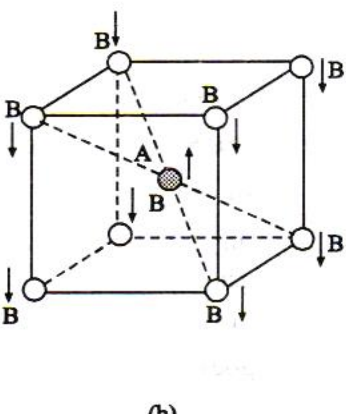


Fig. (a) Alignment of Magnetic Moment in Simple Cubic Crystal at Temperature Below Neel Temperature

(b) Alignment of Magnetic Moment in Body Centered Cubic Crystal

The antiferromagnetic character is explained with a consequence of antiparallel alignment of neighbouring magnetic moment in the crystal. As a result the magnetic moments of *A* and *B* site are cancel with each other. Therefore, net magnetic moment is nearly equal to zero.

3. Properties

1. The dipoles are aligned antiparallel with each other as shown in Fig. Therefore, the resulting net magnetization is zero.

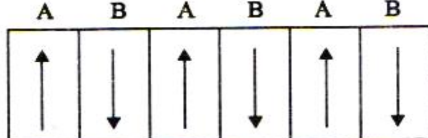


Fig. . Spin Alignment in Antiferromagnetic Material

2. The antiparallel alignment of adjacent dipoles is due to an exchange interaction between them.
3. The magnitude of susceptibility is small and positive.
4. The susceptibility (χ) increases with increase in temperature upto Neel temperature (θ_N). Beyond the Neel temperature (θ_N), the susceptibility decreases with the temperature.
5. In antiferromagnetic material, Neel temperature (θ_N) is the temperature at which susceptibility of the material is maximum.

Examples Ferrous oxide (FeO), Manganese oxide (MnO) and Chromium oxide (Cr_2O_3).

Ferrimagnetic materials (Ferrites)

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Substance which possess a spontaneous magnetization in which the magnetic moments of the two sub lattice are opposite in direction but not exactly equal in magnitude are called "Ferrites".

Ferrites are compounds of iron oxides with oxides of other metals

General Formula: $X^{2+} Fe_2^{3+} O_4^{2-}$

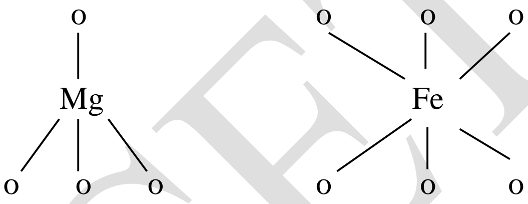
Where $X^{2+} \rightarrow Mg^{2+}, Zn^{2+}, Fe^{2+}, Mn^{2+}, Ni^{2+}$, etc.,

Examples: If X^{2+} is Ni^{2+} then $Ni^{2+} Fe_2^{3+} O_4^{2-}$ is a nickel ferrite.

X^{2+} is Fe^{2+} then $Fe^{2+} Fe_2^{3+} O_4^{2-}$ is a ferrous ferrite.

Ferrites formed usually have a face centered cubic structure of oxygen ions closely packed together with the divalent and trivalent metal ions in the interstitial sites. This structure is called spinal structure. There are two types of ferrites.

(i) Regular spinal ferrite structure
(ii) Inverse spinal ferrite structure



(i) Regular spinal ferrite structure:

In this type each divalent metal ion is surrounded by four O^{2-} Ions in the tetrahedral fashion. It is called "A" site. Totally in a unit cell, there will be 8 tetrahedral sites (8A)

Each trivalent metal ion is surrounded by six O^{2-} Ions in the octahedral fashion. It is called "B" site. Totally in a unit cell, there will be 16 octahedral sites (16B)

Example: $Mg^{2+} Fe^{3+} O_4^{2-}$

Thus in the regular spinal, each divalent metal ion (Mg^{2+}) exists in a tetrahedral form (A site) and each trivalent metal ion (Fe^{3+}) exists in an octahedral from (B site). Hence the sites "A" and "B" combine together to form a regular spinal ferrite structure as shown in figure.

○ Divalent metal ion

⊗ Trivalent metal ion

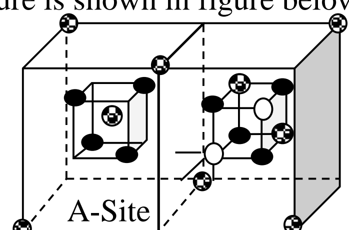
● Oxygen ion

A- Site

(ii) Inverse spinal ferrite structure

Example: $Fe^{3+} [Fe^{2+} Fe^{3+}] O_4^{2-}$

In this, the trivalent metal ions (Fe^{3+}) occupies all the A sites (tetrahedral) and half of the B sites (octahedral) also. Thus the left out B sites will be occupied by the divalent (Fe^{2+}) metal ions. The inverse spinal ferrite structure is shown in figure below.



Types of interaction present in ferrites:

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According to Neel, there are three types of interaction, AA, BB and AB. Out of which AA and BB are negative and considerably weak than AB interaction. Thus the effect of AB interaction dominates and gives rise to antiparallel spin arrangement.

Magnetic Moment of a ferrite molecule:

The orbital and spin magnetic moment of an electron in an atom can be expressed in terms of Bohr magnetron $\mu_B = \left(\frac{eh}{4\pi m}\right)$, saturation magnetization of a ferrite molecule can be calculated from number of unpaired spins of Fe^{2+} and Fe^{3+}

Consider Fe^{3+} [Fe^{2+} Fe^{3+}] O_4^{2-}

(i) Fe^{2+} ions have 6 electrons in 3d shell. Out of '6', 2 electrons are paired and 4 electrons are unpaired.

Therefore, Fe^{2+} gives 4 Bohr Magnetron.

↑↑↑↑↑
↓↓↓↓↓ ↑↑↑↑

(ii) Fe^{3+} ions have 5 electrons are unpaired

Therefore, $Fe3^{+}$ gives 5 Bohr Magnetron

Since we have two Fe^{3+}, totally the Fe^{3+} gives 2x5=10 Bohr magnetron.

Total magnetization = 4+10=14 Bohr Magnetron. But total magnetic moment got only 4.08 μB. Because, in ferrites half of the magnetic spins of Fe_2^{3+} ions are parallel in one direction and the remaining half of Fe_2^{3+} ions are parallel in opposite direction and hence they cancel each other and exists 4 Bohr magnetron which is nearly equal to 4.08 μB.

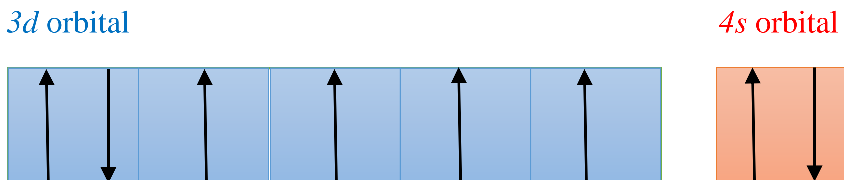
Origin of ferromagnetism and exchange interaction

The ferromagnetic property is exhibited by transition elements such as iron, cobalt and nickel at room temperature and rare earth elements like gadolinium and dysprosium.

The ferromagnetic materials possess parallel alignment of dipoles. This parallel alignment of dipoles is not due to the magnetic force existing between any two dipoles. The reason is that the magnetic potential energy is very small and it is smaller than thermal energy.

The electronic configuration of iron is $1s^2, 2s^2, 2p^6, 3s^2, 3p^6, 3d^6, 4s^2$. For iron , the $3d$ sub shell is an unfilled one. This $3d$ subshell have five orbitals. For iron, the six electron present in the $3d$ subshell occupy the orbitals such that there are four unpaired electrons and two paired electrons as shown in figure.

3d orbital   *4s* orbital



These four unpaired electrons contribute a magnetic moment of $4\mu B$. This arrangement shows the parallel alignment of four unpaired electrons. The parallel alignment of dipoles in iron is

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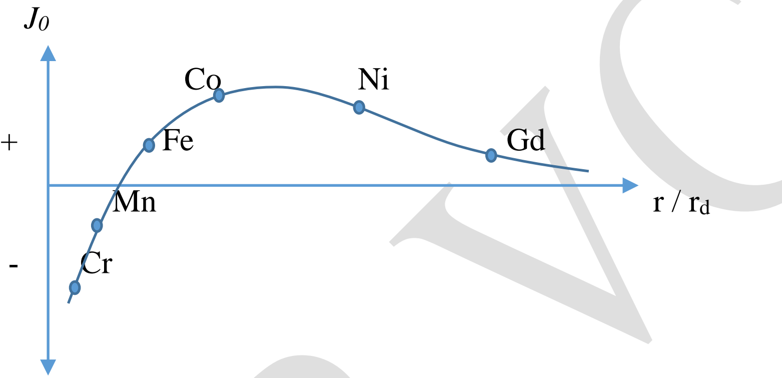
not due to the magnetic interaction. It is due to the Pauli's exclusion principle and electrostatic interaction energy. **The Pauli's exclusion principle and electrostatic interaction energy are combined together and constitute a new kind of interaction known as exchange interaction. The exchange interaction is a quantum mechanical concept.** The exchange interaction between any two atoms depends upon the interatomic separation between the two interacting atoms and the relative spins of the two outer electrons. The exchange interaction between any atoms is given by $E_{ex} = -J_e S_1 S_2$

Where J_e is the numerical value of the exchange integral, S_1 *and* S_2 are the spin angular momenta of the first and second electrons. The exchange integral value is negative for the number of elements. Therefore, the exchange energy value is negative when the spin angular momentum S_1 *and* S_2 are opposite direction. Hence antiparallel alignment of diploe is favoured. This explains the antiparallel alignment of dipoles in antiferromagnetic materials.

In some materials like iron, cobalt and nickel the exchange integral value is positive. The exchange energy is negative when the spin angular momentum is in the same direction. This will produce a parallel alignment of dipoles. A plot between the exchange integral and the ratio of the interatomic separation of the radius of 3*d* orbital (r/r_d) is shown in figure.



For the transition metals like iron, cobalt, nickel and gadolinium the exchange integral is positive, whereas for magnese and chromium the exchange integral is negative. The positive value of the exchange integral represents the material is ferromagnetic and the negative exchange integral value represents the material us antiferromagnetic. In general, if the ratio, $r/r_d > 3$, the material is ferromagnetic, otherwise it is antiferromagnetic.

Weiss molecular Theory of ferromagnetism – Curie temperature

The metals like Fe, Co, Ni etc., exhibit magnetisation even in the absence of external field. Therefore Weiss gave a molecular field theory and postulated the existence of an internal molecular field (H_i). *This internal field is responsible for spontaneous magnetization of a ferromagnetic material, so that only the material possess magnetization even in the absence of an external field.*

The net or effective magnetic moment $H_c = H + H_i$ (1)

Where H is external field, H_i is the internal molecular field and is proportional to the intensity of magnetization

1.e., $H_i \propto I$ (2)

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$H_i = \lambda I$ (3)

Where λ is Weiss constant

Substituting equation (3) in (1), we get

$H_e = H + \lambda I$

From Langevin theory, the intensity of magnetization of the ferromagnetic material is given by

$$I = \frac{N\mu^2}{3K_BT}(H + \lambda I) \quad (4)$$

Where N is the number of atoms

$$I = \frac{HN\mu^2}{3K_BT}\left(1 + \lambda\frac{I}{H}\right)$$

(or) $$\frac{I}{H} = \frac{N\mu^2}{3K_BT}\left(1 + \lambda\frac{I}{H}\right)$$

$$\chi_m = \frac{C}{T}[1 + \lambda\chi_m] \qquad \left[\because \frac{I}{H} = \chi_m\right] \quad (5)$$

Where $C = \frac{N\mu^2}{3K_B}$

Equation (5) can be rewritten as

$$\chi_m = \frac{C}{T} + \frac{C}{T}\lambda\chi_m$$

(or) $$\chi_m = \frac{C}{T - \lambda C}$$

(or) $$\chi_m = \frac{C}{T - \theta} \quad (6)$$

This is known as Curie – Weiss law and θ is known as curie temperature.

Equation (6) has three special cases

Case 1: when $T = \theta$, $\chi_m \rightarrow \alpha$

The material is ready to attain external magnetization

Case 2: when $T > \theta$, $\chi_m = 1/+ve$ i.e., χ_m is positive

In this case, the thermal agitation opposes the tendency of Weiss molecular field to align the molecular magnets. So it becomes paramagnetic above Curie temperature.

Case 3: when $T < \theta$, *the material behaves as ferromagnetic material* because at lower temperature Weiss molecular field energy is high and sufficient to overcome the thermal agitation.

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Curie temperature

Ferromagnetic material have a critical temperature below which they behave as ferromagnetic and above which they behave as paramagnetic. This critical temperature is known as ferromagnetic curie temperature.

Spontaneous and Saturation magnetization

The molecular magnets in the ferromagnetic material is aligned in such a way that, they exhibit a magnetization even in the absence of an external magnetic field. This is called spontaneous magnetization.

We know that, $H_c = H + H_i$

Here $H = 0$, therefore $H_e = H_i$

(or) $H_e = \lambda I$

Where I is spontaneous magnetization.

Temperature dependence of spontaneous magnetization

When the external field is zero, $H_e = \lambda I$ (1)

From the Langevin theory, we can write intensity of magnetization I as

$I = I_s L(\alpha)$ (2)

Where I_s *is the* saturation magnetization

For Ferro magnets $\alpha = \frac{\mu H_e}{K_B T}$ [since $H = 0$]

(or) $H_e = \frac{\mu\alpha}{K_B T}$ (3)

Comparing equation (1) and (3), we get

$$\lambda I = \frac{\alpha K_B T}{\mu} (or) I = \frac{\alpha K_B T}{\mu\lambda} \quad (4)$$

We know $I_s = N\mu$ (5)

Dividing equation (4) by (5), we have

$$\frac{I}{I_s} = \frac{\alpha K_B T}{N\mu^2\lambda} = \frac{\alpha}{3}\left(\frac{T}{\theta}\right) \quad \left[\because \theta = \frac{N\mu^2\lambda}{3K_B}\right]$$

(or) $\frac{I}{I_s} = f\left(\frac{T}{\theta}\right)$ [where $f = \alpha/3$]

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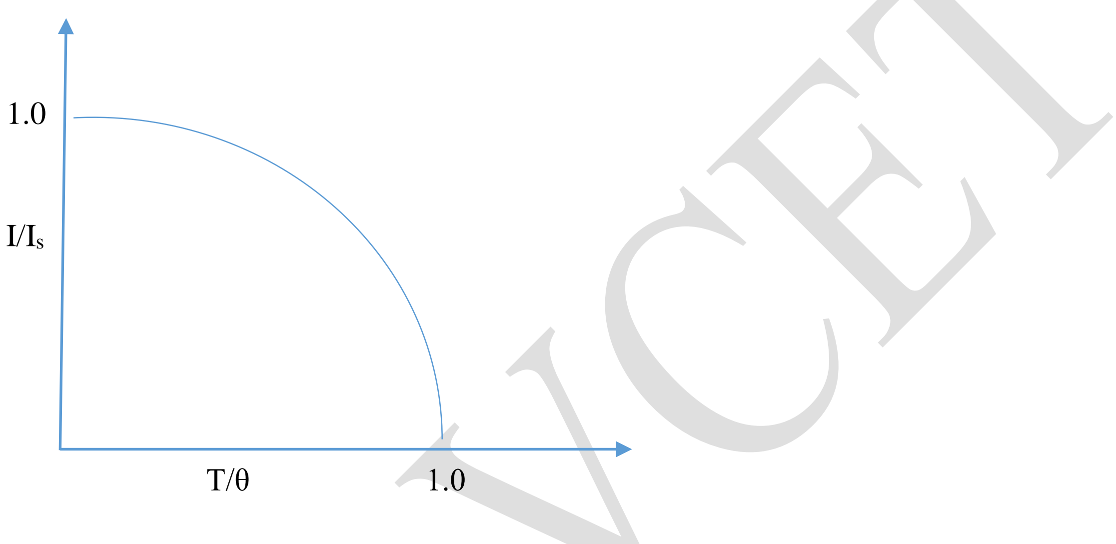
A graph is plotted between I/I_s as a function of T/θ as shown in figure. From the graph, we infer that

(i)**when the temperature is low,** Weiss field overpowers the thermal energy and it gives rise to maximum magnetization

i.e., $I/I_s = 1$

(ii) **when the temperature is increased** thermal energy increases which randomises more and more of the parallel spins and at curie temperature (T = θ), all the parallel alignment of spin vanishes give rise to zero value of spontaneous magnetization and the Material is to highly susceptible to get the external field. Thus, the substance become paramagnetic.



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Explain the writing and reading of data in magnetic hard disk using Giant Magnetoresistive (GMR) sensor?

Principle

In hard disk drives, the binary data in terms of zero's (0) an one's (1) are stored by inducing magnetic moment in a thin magnetic layer and GMR effect is used as the principle to read the data in HDD. Here zero (0) represents missing transition and one (1) represents transition in the medium.

Construction

The HD consists of recording medium madeup of thin layer of magnetic garnets grown over the substrate. The GMR sensor, which is made up of ferrites and antiferromagnetic materials is used as reading element. The writing element is madeup of inductive magnetic transducer. The writing element and the GMR sensor shall be made to slide over the recording media in the longitudinal direction as shown in figure. Hence this method is also called as longitudinal recording. The flow of current through the GMR sensor and writing element shall be adjusted and inturn the magnetization is sensed (or) controlled in the recording media.

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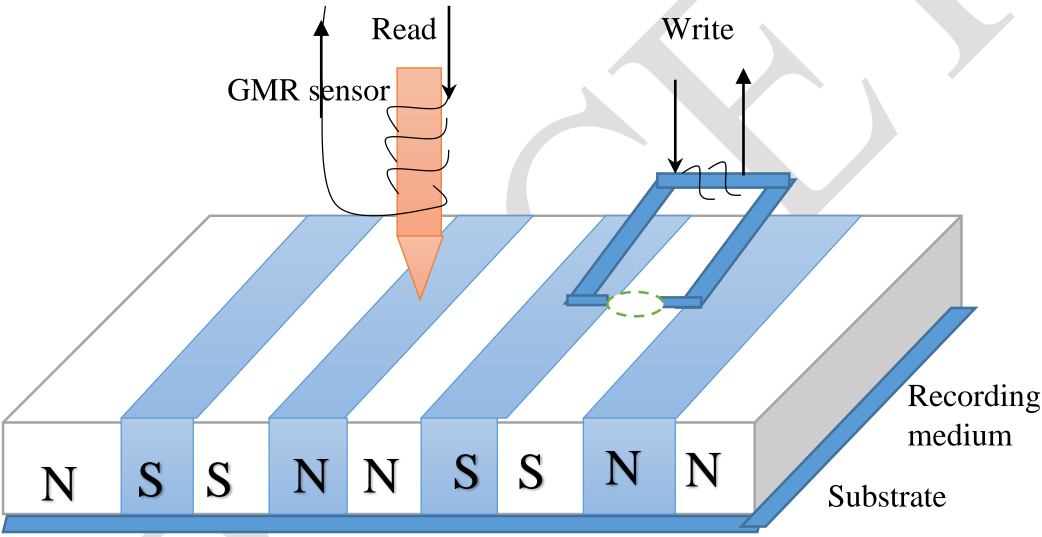
Working

Writing / Storing

1. Initially the current is passed through the writing element and a magnetic field is induced in between the gap of the inductive magnetic transducer.
2. During writing, the amplitude of current is kept constant, and the direction of current is reversed.
3. Due to reversal of current, the magnetization orientation is reversed in the recording medium i.e., from south → North as shown in figure
4. When the induced magnetic field is greater than the coercivity of the recording media, then data is recorded in the form of 1.
5. Thus one (1) is stored as data in the recording medium as a magnetic transition.
6. When there is no magnetic transition, then it is referred as zero (0).
7. In this way the zero's (0's) and one's (1's) are stored in the recording medium.



Reading / Retrieving

8. Giant Magnetoresistive (GMR) effect is the principle used to read / retrieve the data from the recording medium.
9. When the GMR sensor is made to move near the recorded medium, then the resistance of the GMR sensor varies with respect to the orientation of the magnetic moments as follows.
10. When the layers are magnetised in parallel manner, then the resistance in the GMR sensor is minimum and therefore maximum current flows through the sensor, which represents the data as one (1)
11. When the layers are magnetised in antiparallel manner, then the resistance in the GMR sensor is maximum and therefore minimum(or) almost no current flows through the sensor, which represents the data as zero (0)
12. Therefore with the help of the reading current, the zero's (0's) and one's (1's) can be retrieved from the magnetic hard disk drive.

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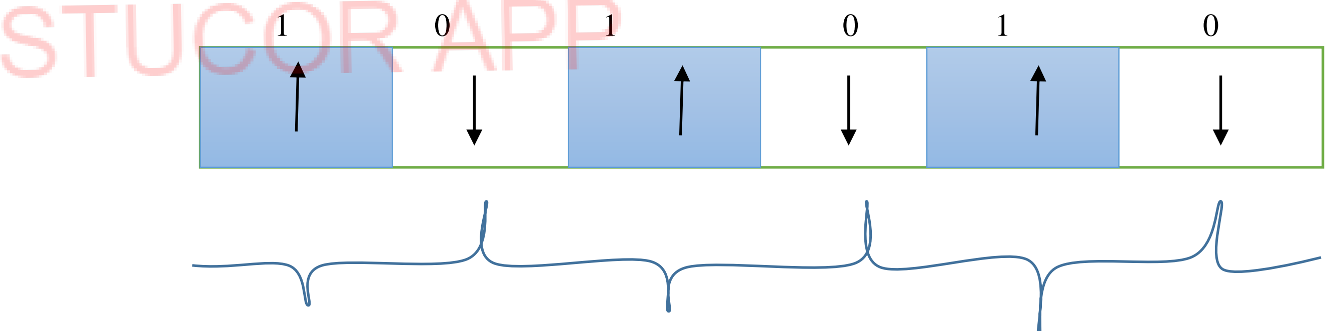

Advantages

- HDD can store the data in terabytes
- It has very large storage capacity
- It is compact in size and can be easily transferred from one place to another.
- The size of recording medium is reduce up to few nano meter range using nanotechnology
- GMR sensor are non-diffusive and are very sensitive in reading

Disadvantages

- HDD is slower than soli state drives
- Consume large power
- Data may be corrupted due to thermal radiation
- HDD has bulkier form factor
- GMR noise ratio is high for nano size recording media

Applications

- Used as storage devices in cloud applications
- Used in coding and signal processing units
- Used in control systems, Nano electronics, etc.,

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4. Optical Properties of Materials

Part – A

1. **What are optical materials?**
   The materials which are sensitive to light are known as optical materials. These optical materials exhibit a variety of optical properties.
2. **What are the types of optical materials?**
   Based on nature of propagation of light, the optical materials are classified as
   (i) Transparent
   (ii) Translucent
   (iii) Opaque
3. **What is transparent materials?**
   The materials which transmit light with little absorption and reflection. In these materials, one can clearly view the object through the material
4. **What is translucent materials?**
   The incident gets scattered within the material and the diffused light is transmitted with the other side of the material. One cannot clearly view the object through this material
5. **What is opaque materials?**
   The material which absorbs the visible light are called opaque. Here, after interaction of light with material, the light gets reflected or absorbed.
6. **What is meant by total incident flux of photon?**
   It is the sum of the fractional ratios of light transmitted, reflected and absorbed to the energy flux per unit area (J/m^2S).
7. **Define scattering of light**
   It is process by which the intensity of the wave attenuates as it travels through the medium.
8. **Define carrier generation and recombination process.**
   Generation is the process of creating electron and hole pair per volume-second. While the recombination is the process of annihilating the electron and hole pair per unit volume – second.
9. **List out the types of carrier generation?**
   (1) Photon generation
   (2) Phonon generation
   (3) Impact Ionization
10. **List out the types of Recombination?**
    (1) Radiative recombination
    (2) Shockley - Read - Hall recombination
    (3) Auger recombination
11. **What is the effect of optical absorption in semiconductors?**
    (1) It forms excitons
    (2) It produce photoconductivity
    (3) It excites the crystal lattice vibrations
    (4) It excites the free electrons and holes

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12. Define trap, its origination and types

It is an intermediate energy levels presents in the energy band gap. These traps arises due to the presence of impurity atoms and imperfections in the crystal. There are two types of trap viz. (1) Trapping centre an (2) Recombination centre

13. Differentiate Trapping centre and Recombination centre

S.No	Trapping centre	Recombination centre
1.	It is a type of trap which captures an electron (or) hole and then reexcite to free state	It is type of trap in which electron an hoke recombines with eachother to produce phonons
2.	Here the charge carriers are temporarily trapped	Here the charge carriers are permanently trapped

14. What is meant by injection luminescence? Give example

When the majority carriers are injected from *p* to *n* and *n* to *p* region, they become excess minority carriers. Then these excess minority carriers diffuses away from the junction and recombines with the majority carriers in *p* and *n* regions and emits light. This phenomenon is known as injection luminescence. Example: LED

15. What is photo diode?

It is a reverse biased P – N junction diode which responds to light absorption

16. Explain the principle of photo diode?

When the light is incident on the depletion region of the reverse biased *P – N* junction, the concentration of minority charge carriers increases. Therefore, reverse saturation current increases.

17. What is solar cell?

It is basically a large area photo diode which converts sunlight (solar energy) directly in to electricity (electrical energy), with larger efficiency of photon absorption..

18. Explain the term exciton?

An exciton can form when a photon is absorbed by a semiconductor. This excites an electron from the valence band into the conduction band. In turn, this leaves behind a positively charged electron hole . The electron in the conduction band is then effectively attracted to this localized hole by the repulsive Coulomb forces from large numbers of electrons surrounding the hole and excited electron.

19. What is LED?

It is a *P-N* junction which emits light when it is forward biased.

20. Why is the shape of LED made hemispherical (or) why dome shape LED is preferred than a planar LED.

In planar LED's the emitted light strikes the material interface at an angle greater than the critical angle and the reflection loss will be very high.

Therefore, to minimise the reflection loss, hemispherical dome shape LED is made, in which the angle at which the emitted light strikes the interface can be made less than the critical angle.

21. What is an OLED?

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

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22. What is the principle of OLED?

An electron moves from the cathode to the emissive layer and the hole moves from the anode to the conductive layer and they recombine to produce photons. This is the principle used to emit light in OLED.

23. Mention any four types of photo diodes

(1) *PIN* photo diode
(2) Avalanche photo diode
(3) Schottky photo diode
(4) Solar cell

24. What is meant by optical data storage?

The process of storing the data in the storage medium using optical phenomenon is called optical data storage

Example: CD, DVD, etc.,

25. What is the principle of CD?

The data to be stored is first converted in to binary form (0 or 1) and stored in the form of reflecting and non-reflecting micro points in spiral path on a disc. During the read out process, variation in the reflected intensity of laser is converted back to data.

26. What is laser diode?

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

27. List out the various optical data storage techniques

(1) CD - ROM
(2) CD - RW
(3) DVD
(4) Blu-ray Disc
(5) Magneto optical disc
(6) Holography.

28. What are the advantages of optical data storage?

(1) Immune to dust
(2) Relatively inexpensive
(3) Storage capacity is high
(4) It is removable

29. What are activators and co activators?

The impurity ions which leads to the production of traps are called activators.

The ionic charges present along with the impurities are called co-activators

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Part – B

1. Describe absorption and emission of light in metal, insulator and semiconductor

Metals

Metals are **opaque** because of the incident light radiation excites electrons into unoccupied energy states above the Fermi energy. As a result the incident radiation is absorbed. Total light absorption is within a very thin outer layer usually less than 0.1 μm. Hence metallic films thinner than 0.1 μm are capable of transmitting visible light. Moreover metals are **opaque** at lower frequencies (radio frequency to mid of ultraviolet radiation) and **transparent** to high frequency

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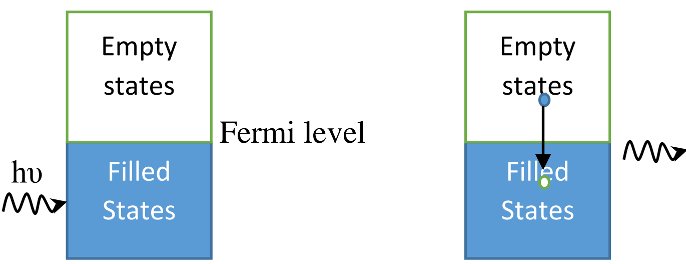
X – rays and γ rays. Most of the absorbed radiation is reemitted from the surface in the form of visible light of same wavelength which appears as **reflected light**. The reflectivity in the most of the materials will be between 0.9 and 0.95. The colour of a metal is determined by the wavelength distribution of the reflected radiation.



Insulators

Absorption of a light photon may occur in an insulator. It results in excitation of an electron from valence band to conduction band after crossing the energy gap E_g. A free electron in the conduction band and a hole in the valence band are created. The excitation of an electron due to absorption of light can take place only if the light photon energy ($\Delta E = h\upsilon$) is greater than that of band gap E_g.

i.e., $\Delta E = h\upsilon$.

Here, light photon absorption takes place only when $h\upsilon > E_g$

(or) $hc/\lambda = E_g$.

Thus, for a visible light the wavelength is typically of about 0.4μm, then the band gap energy for the light is about 3.1 eV. Thus no visible light is absorbed by materials having band gap energies greater than about 3.1 eV. These materials appears transparent and colourless if they are high purity state.

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Semiconductors

In semiconductors, light photons is absorbed in several ways. In intrinsic semiconductors light photons is absorbed to create electron - hole pairs. This absorption causes electrons to jump across the energy band gap from the valence band to the conduction band. Hence the excitation of electrons due to absorption can takes place if the photon energy is greater than that of the band gap E_g, The maximum wavelength for visible light λ_{max} is about 0.7μm. Therefore the minimum bandgap energy $E_{g\,(min)}$ for which there is absorption of visible light is given by$E_{g\,(min)} = hc / \lambda_{max}$

Here, $E_{g\,(min)}$ is found to be 1.8 eV. Hence all visible light is absorbed by those semiconductors having band gap energies less than about 1.8eV, thus these semiconductors are **opaque**.

In extrinsic semiconductors, the presence of acceptor and donor impurities creates new energy levels namely acceptor level (p - type) and donor level (n - type). These impurity level lie within the bandgap of the material. Light radiation of specific wavelength may be absorbed as a result of electron transitions from or to these impurity levels within the band gap.

2. Explain carrier generation and recombination in semiconductor

Carrier generation:

It is the process of generating number of hole - electron pairs per unit volume second. Basically there are three types of carrier generations.

*(i) **Photo generation***

E_C

$h\upsilon$

E_V

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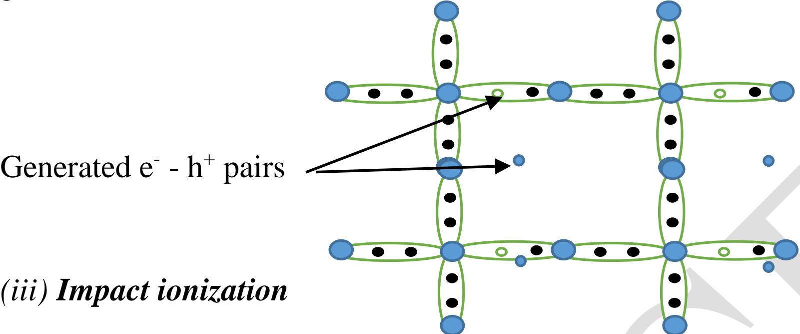
When a photon is incident with energy $h\upsilon$ greater than the energy of band gap of a semiconductor, then the electrons in valence band absorbs this photon and jumps to conduction band thereby generating electron - hole pair. For different wavelengths of light with different energies it can take an electron in higher conduction band states.

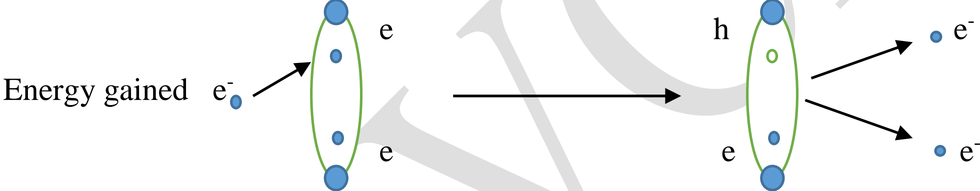
(ii) ***Phonon generation***

When a semiconductor is under thermal excitation, with increase of temperature of the semiconductor, lattice vibrations increase which give rise to more phonons. Due to more lattice vibrations, covalent bonds in the semiconductor break down and electron - hole pairs are generated.



(iii) ***Impact ionization***

When a semiconductor is under an electric field, one energetic charge carrier will create another charge carrier. For a very high electric field, it results in an avalanche breakdown.

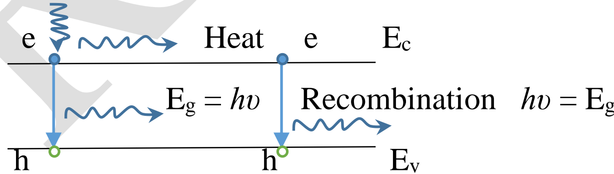


Recombination:

It is a process in which the electron – hole pair are annihilated during recombination per volume second. Recombination occurs in three ways:

(i) ***Radiative recombination***

This process occurs in direct band gap semiconductor. When an electron in the conduction band minimum falls to valence band maximum without change in momentum. One photon of energy $h\upsilon$ is emitted. This is direct recombination. Here the electrons in the highest energy states of conduction band will come back to conduction band minimum by non radiative transition (heat).



(ii) ***Shockley - Read - Hall recombination***

In this process, electrons from the conduction band minimum or holes from the valence band maximum are come to a defect level intermediate between E_c and E_v by radiation energy as photons or phonons. These intermediate levels are called trapping level. Hence either the electron or the hole from the trapping level returns to the valence band or conduction band. They are not set free & hence it is said to be trapping level. Generally this process occurs in impure semiconductors.

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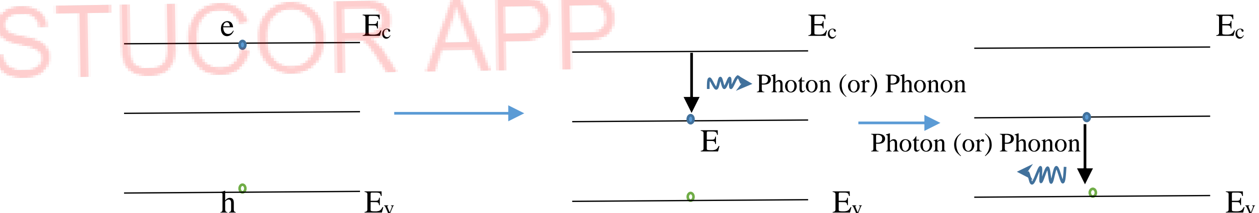
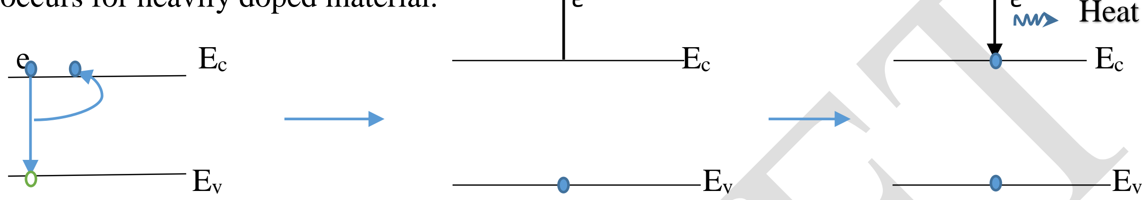


*(iii) **Auger recombination***

Here three carriers are involved. i.e., the electron and hole recombine may have an energy which is given to the third free electron in the conduction band. Then the excite third electron comes back to the conduction band edge by emitting energy as heat. Generally an Auger recombination occurs for heavily doped material.



3. Describe the construction and working of photodiode

It is a reverse biased *p* - *n* junction diode which responds to light absorption.

Principle

When light is incident on the depletion region of the reverse biased *pn* junction, the concentration of minority carrier increases. Therefore, reverse saturation current increases.

Construction

A photo diode consists of a *p* - *n* junction which is placed in a transparent plastic capsule as shown in figure. Light is allowed to fall on the surface of the junction. The symbol of the photodiode is shown in figure.

Working

When the photo diode is kept under dark condition and a voltage is applied, then a constant current independent of reverse bias voltage is obtained. This reverse saturation current is due to thermally generated minority carriers. It is called dark current (I_d) and is proportional to the concentrations of minority carriers

When the light falls on the diode surface, additional electron - hole pairs are generated. These injected minority carriers diffuse to junction and contribute to the additional current.

Thus under reverse bias conditions, total reverse current is given by $I = I_d + I_s$

Where I_s is the short circuit current and it is proportional to the intensity of light. The I - V characteristic curve of photo diode shows that

(1)The current increases with increase in the level of illumination for a given reverse voltage.

(2)Only for the dark current at zero voltage the current is zero.

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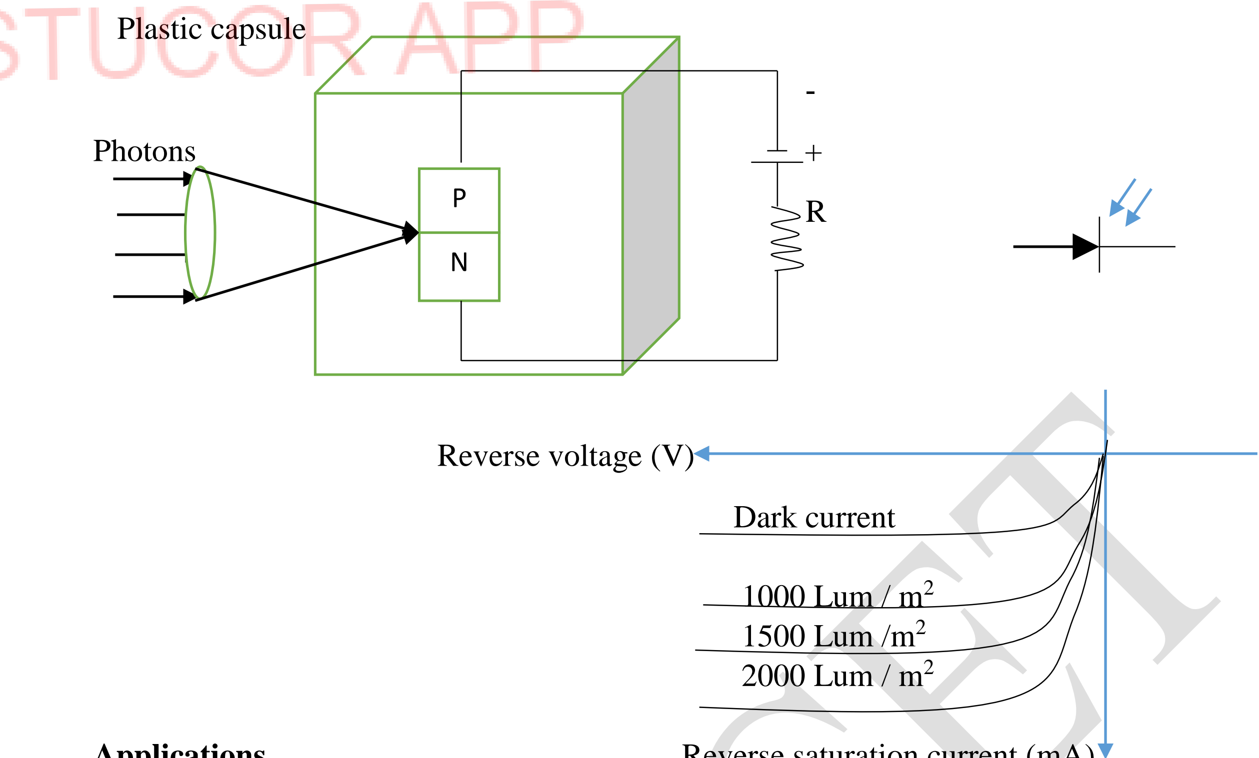


Applications

Light detection systems

Reading of sound track in film

Light operated switches

Used as variable resistance device controlled by light intensity

Used to switch on the current at a very fast rate.

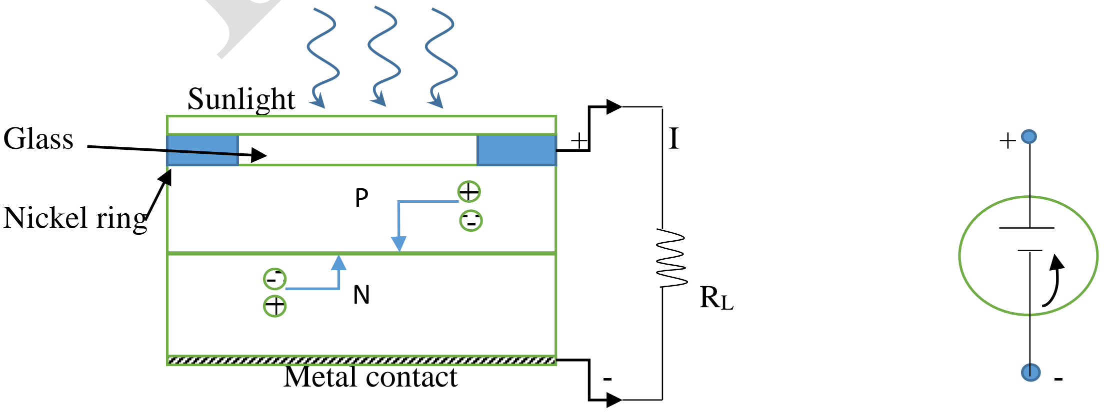
4. Explain the construction and working of solar cell. Also discuss the advantages, disadvantages and its applications.

It is a *p* - *n* junction diode which converts solar energy (light energy) in to electrical energy.

Construction

It consists of *p* - *n junction* diode made of silicon. The *p* - *n* diode is packed with glass window on top such that light may fall up on *p* and *n* type materials. The symbol of the solar cell is shown in figure.

The thickness of *p* and *n* regions are kept very small. As a result electrons or holes generate near the surface of *p* or *n* region can diffuse to the junction before they recombine. A nickel ring is provided at the top of the *p* layer which acts as the positive output terminal. A metal contact at the bottom serves as the negative output terminal.



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Working

When light radiation from sun falls on the *p* - *n* junction diode, the photon energy is sufficient to break the covalent bond and produce electron hole pair. These electrons and holes reach the depletion region by diffusion and they are separated by the strong barrier electrical field existing there.

The minority carrier electrons in the *p* - side cross the barrier potential to reach *n* side and the holes in *n* - side move to the *p* - side. Their flow constitutes the minority current which is directly proportional to the illumination of light and the surface area being exposed to light.

The electrons and holes accumulated on either sides of junction leads to open circuit voltage V_{oc} as a function of illumination. In case of silicon solar cell, V_{oc} is typically $0.6V$ and the short circuit current is about 40 mA/cm^2 in bright noon day sun light. The *I* - *V* characteristics of solar cell shows maximum power output when the solar cell is opened at the knee of the curve

Advantage:

(1) It operates with fair efficiency
(2) It can be mass produced
(3) It has high power capacity per weight
(4) Its size is small and compact.

Disadvantage

(1) Solar energy is not available during winter season and night time
(2) We need an additional equipment like inverter to store the electrical energy
(3) The output which is in DC is converted to AC

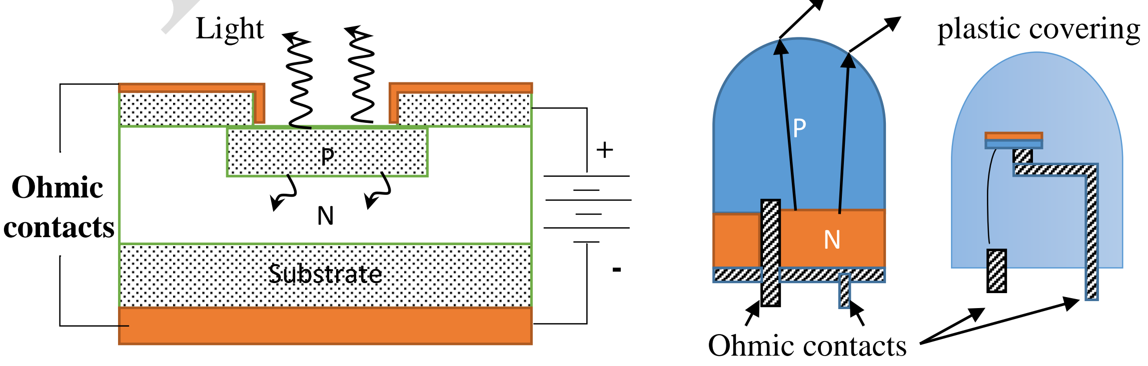
Uses

(1) It is used in satellites and space vehicles to supply power to electronic and other equipment's
(2) It is used to give power to the calculators and watches
(3) They are used to provide commercial electricity.

5. Explain the construction and working of a LED with energy band diagram. How the Planar LED is differ from dump shaped LED?

Principle

Injection luminescence is the principle used in LED. When *p* - *n* junction (LED) is forward biased, the majority carriers moves from *p* to *n* region and vice versa. These excess minority carriers diffuse through the junction and recombine with majority charge carriers respectively to produce (light) photons.



Fabrication

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Here *n* - type layer is grown on a substrate and *p* - type layer is deposited above it by diffusion. *p* type is grown as a top layer because of the recombination process takes in this region. For maximum light emission, a metal film anode is deposited at the outer edges of the *p* - type layer and the bottom of the substrate is coated with gold film (metal).This metal surface reflects the light and also act as cathode.

Working

(1) When a *p* - *n* junction is forward biased, the barrier width is reduced, raising the potential energy on the *n* side and lowering that of the *p* - side
(2) The free electron and hole have sufficient energy to move to the junction region.
(3) If a free electron recombine with a hole it will release a photon (light)
(4) This photons created in LED are due to electron and hole recombination that are injected into the junction by a forward biasing voltage.

Advantages

(1) Smaller in size
(2) Cost is very low
(3) Long life time
(4) Available in different colour at low cost
(5) Operates at very low voltage
(6) Fast response time (10^{-9} seconds)
(7) Operated at wide range of temperatures (0 ~ 70°C)
(8) Dome shaped LED has less scattering loss

Disadvantages

(1) Power output is low
(2) Intensity is less than laser
(3) Light cannot travel through long distance
(4) Light output in incoherent and not in phase

Dump shaped LED

In planar LED, the reflection loss is more because of the emitted light strikes at the materials surface at an angle greater than critical angle and suffers total internal reflection. Hence it will not come out of the interface and the light is lost. Hence by making *p* type in hemispherical shape or by covering the *p* - *n* junction diode by a hemispherical plastic medium of higher refractive index, the reflection loss is eliminated.

6. Write a brief note on OLED?

Principle

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

Fabrication

The 2 - layer OLED consists of two organic layers in between a cathode and an anode.

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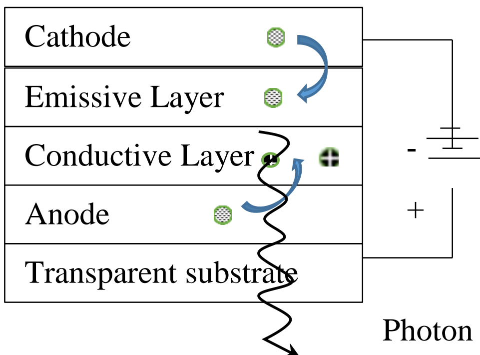
The two organic layers are (i) emissive layer (ii) conductive layer, made up of different conductivities. All the layers are grown over a transparent substrate, through which the light has to be emitted. Necessary biasing is given or OLE in such a way that the anode is given positive and the cathode is given negative as shown in figure.



Working

(1) Voltage is applied across the OLED
(2) Due to the applied voltage, the cathode gives electrons to the emissive layer
(3) The anode withdraws the electron from the conductive layer and creates a hole in the conductive layer as sown in figure.
(4) That is the anode gives (electron – hole) **polarons** a quasi-particle - a positive (or) negative ion slightly attracted to a negatively (or) positively charge carriers respectively.
(5) Soon, the emissive layer has large number of negatively charged particles and the conductive layer has large number of positively charges particles.
(6) Due to electrostatic forces between these electrons and holes, they come closer and recombine with eachother.
(7)In OLED, the recombination occurs closer to the emissive layer, because in organic semiconductors, holes moves faster than electrons.
(8)This, the recombination of electrons and holes produces photons and is emitted through the transparent substrate as shown in figure.

Advantages

(i) It is very thin and more flexible
(ii) They are light in weight
(iii) Light emission is brighter than normal LED’s
(iv) The conductive and emissive layers can be increased to increase the efficiency of OLED
(v) OLED does not require backlighting like LCD
(vi) They have large field of view (about 170°C)

Disadvantages

(1) Manufacturing cost is high
(2) It get damaged easily when water falls on it
(3) Blue OLED has less life time than Red OLED

Applications

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(1) It is widely used in cell phones, digital cameras, etc.,
(2) It is used in TV screens, computer monitors
(3) Use in automotive dash boards, backlights in cars

Types

(1) Polymer Light Emitting diode (PLED)
(2) Patternable Organic Light Emitting Diode (POLED)
(3) Transparent Organic Light Emitting Diode (TOLED)
(4) Stacked Organic Light Emitting Diode (SOLED)
(5) Inverted Organic Light Emitting Diode (IOLED)

7. Describe the construction and working of a semiconductor laser (homojunction) with necessary diagrams. Also compute its advantages, disadvantages and applications?

Principle

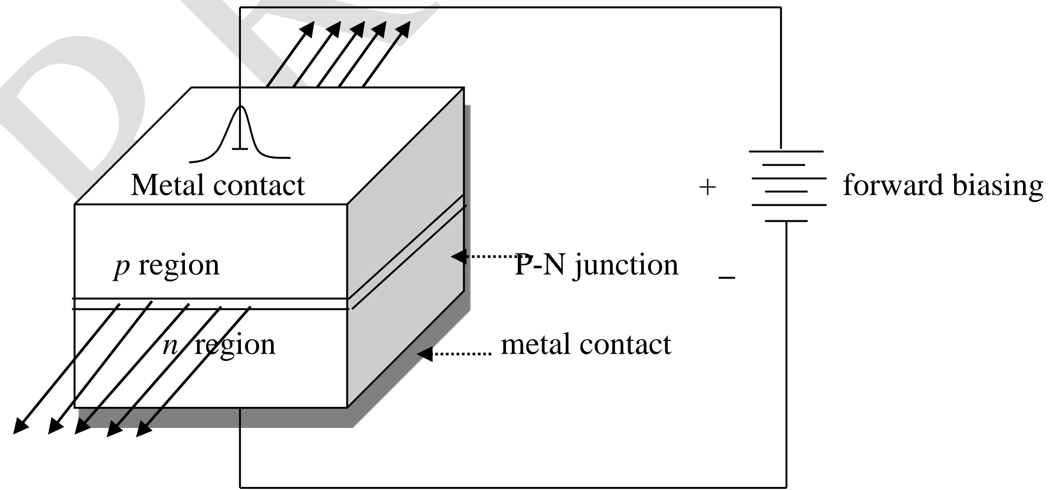
When a p - n junction diode is forward biased the electrons from n - region and the holes from p - region cross the junction and recombine with each other. During the recombination process the photons (light radiation) is released from direct band gap semiconductor (Eg: GaAs) which stimulates other electrons and holes to recombine and hence the stimulated emission takes place which produces the laser

Construction

The basic construction of a semiconductor homojunction diode is shown in the figure

Laser output

The active medium is a *p* - *n* junction diode made from a single crystal of GaAs. This crystal is cut in the form a platelet of thickness 0.5mm.this platelet has an electrical (*n*-type) and hole conductivities (*p*-type)



The photon emission is stimulated by a thin layer of PN junction. The potential difference is applied to the homojunction diode through the metal contact .the end faces of the junction are polished and made parallel to each other. They act as optical resonator (the diode has high refractive index) where the laser comes out.

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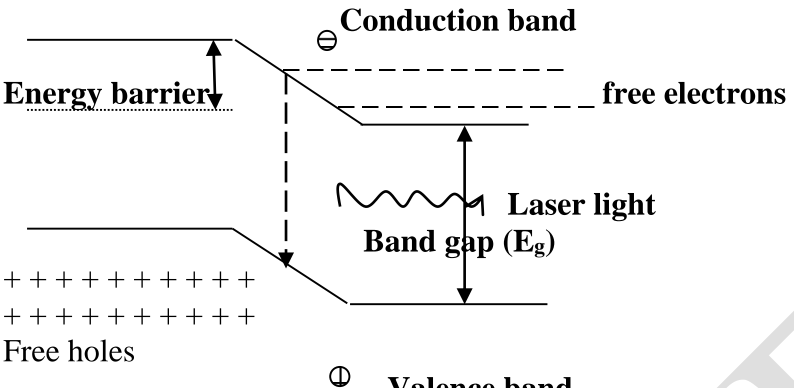
Working

Figure shows the energy level diagram. When the diode is forward biased using the applied potential difference, the electron and holes are injected in to the junction where the concentration of holes in p – region and electrons in n - region strengthens. After the population inversion condition is achieved, the electrons and holes are recombined to produce a radiation in the form of light



When the forward biased voltage is increases, the emitted photon multiplies and triggers these recombining photons in phase. These photons moving at the plane of junction travels back and forth by reflection between two sides of the junction and grows in strength. After gaining enough strength it emits a laser beam of wavelength 8400A°. The wavelength of emitted radiation depends on (i) band gap & (ii) the concentration of donor & acceptor atoms. The wavelength of laser light is given by $E_g = h\upsilon$ (or) $\lambda = \frac{hc}{E_g}$ where E_g – band gap energy & $\upsilon = c / \lambda$

Characteristics

01.	Type	Solid state homojunction semiconductor laser
02.	Active Medium	PN junction GaAs diode
03.	Pumping Method	Direct conversion method
04.	Power output	1mW
05.	Nature of Output	Continuous (or) Pulsed
06.	Wavelength	8400 A°

Advantages

(i) It is small in dimension and compact
(ii) It exhibits high efficiency
(iii) The laser output can be increased easily by controlling junction current
(iv) It requires little auxiliary equipment

Disadvantages

(i) It is difficult to control mode pattern and structure of laser
(ii) Output beam has large divergence
(iii) Monochromacity is poorer than other type of laser
(iv) Threshold current density is large

Applications

(i) It is used in optical communication
(ii) It is used to heal the wounds by infrared radiation

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(iii) It is used in CD writing and reading

8. Describe the construction and working of a Heterojunction semiconductor laser with necessary diagrams. Also compute its advantages, disadvantages and applications?

Principle

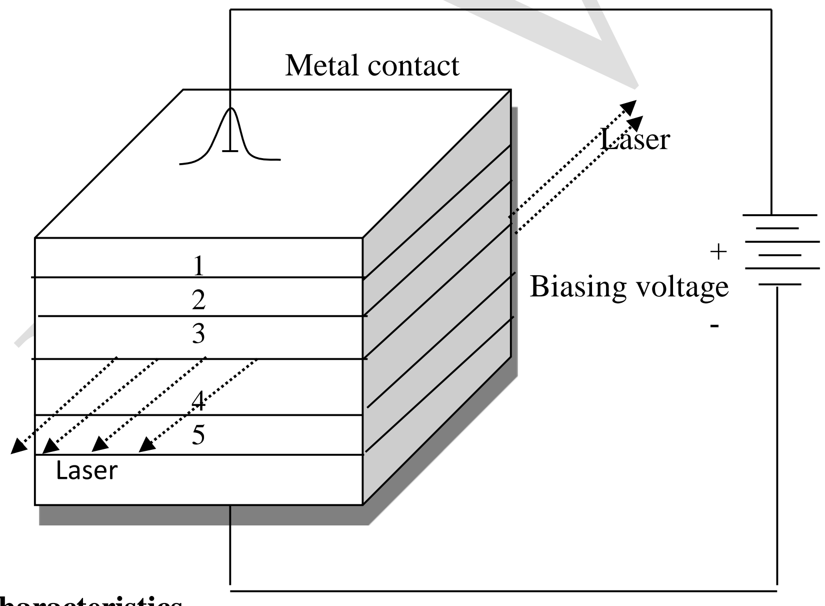
When a p - n junction diode is forward biased, the electrons from n- region and holes from p - region recombines with each other at junction and emits photons in the form of light at certain direct band gap semiconductor

Construction

This laser consists of five layers as shown in figure. A layer of GaAs - *p* type act as active medium (3rd layer).This layer is sandwiched between two layer of GaAs - *p* type & GaAs -*n* type with wide band gap. The electrical voltage is applied at the extreme layers and the 3rd & 4th layers are polished and made parallel to each other. They behave as optical resonator

Working

When the PN junction is forward biased, the electrons and holes are injected into junction. The region around junction has large no of electrons in conduction and large no of holes in valence band. Hence the population inversion is achieved. As a result recombination electrons and holes produce photons as light radiation. When the forward biasing voltages increases, the stimulated recombination increases the intensity of photons and they are in phase. This photon travels back and forth at junction due to reflection and grows in strength. A coherent laser beam of wavelength 8000 A° is emitted at the junction.



Layer1: GaAs - *p* type
Layer2: GaAs - *p* type
Layer3: GaAs - *p* type
Layer 4: GaAs - *n* type
Layer 5: GaAs - *n* type

Characteristics

01.	Type	Solid state Heterojunction semiconductor laser
02.	Active Medium	*p* - *n* junction made from different layers
03.	Pumping Method	Direct conversion method
04.	Power output	1mW
05.	Nature of Output	Continuous
06.	Wavelength	8000 A°

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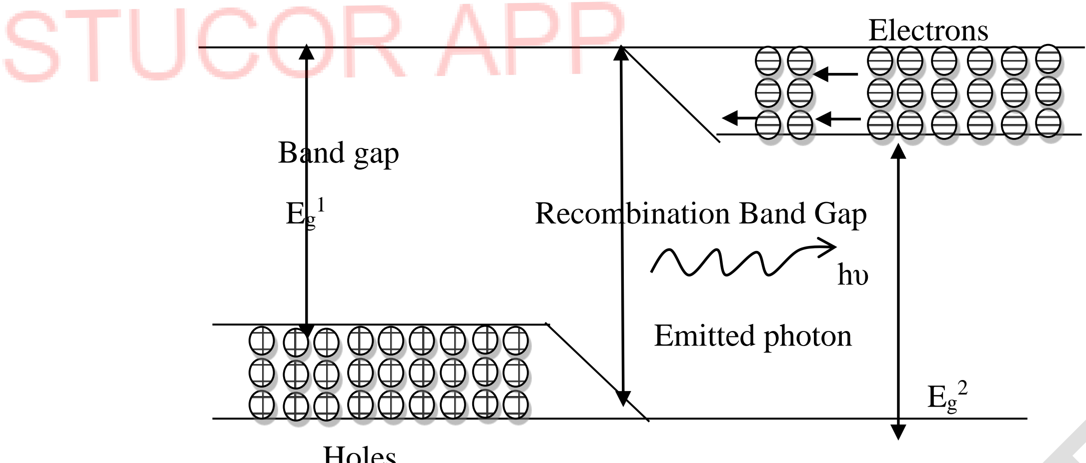

Advantages

(i) It produces continuous wave output
(ii) The power output is high

Disadvantages

(i) It is difficult to grow different layers of a *p -n* junction
(ii) The cost is high

9. Explain optical storage techniques?

The optical data storage techniques resulted in increased storage capacities after the invention of laser. In general they are classified as surface storage and volume storage.

Optical tape

For many years photosensitive film roles are used as optical tapes for recording optical information. Even acoustical information are recorded in such tapes as sound tracks.

Optical Disc (CD)

Principle

The data to be stored is first converted into binary form as 0's and 1's. it is then store in the form of reflecting and non-reflecting micro points in spiral path on a disc. During the read-out process, variation in the reflected intensity of laser is converted back to data.

This optical disc is further classified as *reading only* and *Recording and reading type* based on their storage technique and capabilities. However in either type's laser diode, lenses and photodiodes are used.

During recording, it change electrical information into optical information and then records the information on the optical disc. While reading the head optically reads the recorded information and changes the optical information in to electrical information. The commercial system make use of discs that are 90, 120, 130 and 300nm in diameter. A mini disc, 64nm in diameter is also used for digital audio.

CD audio

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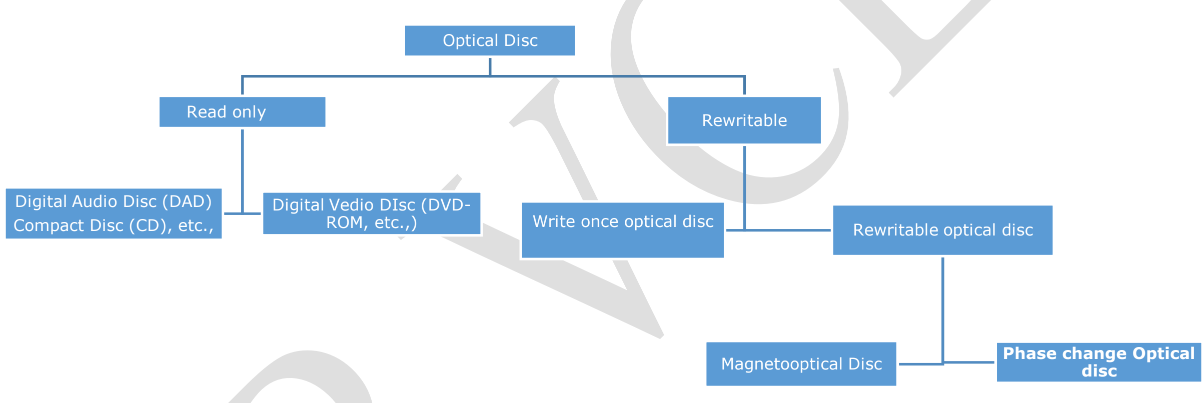
The substrate of the disc is either plastic or photo polymer. First audio signal to be stored is stored is converted into binary. This is then stored in the form of reflecting and non – reflecting micro points in spiral path on a on a metallic master using sharply focussed laser beam. The digital data is pressed onto the substrate by injection moulding. Thus mass production of the CD form base on this concept.

CD ROM

This is similar to that of CD audio with a difference that here in this case video signal is converted into binary and stored in a metallic master. The data thus replicated from the master on a plastic substrate can be read any number of times but cannot be changed and hence this name.

CD – WORM

In this the active layer is chemically coated on the substrate. The laser pulses generated in the CD writer burns the chemical coating and there by creates reflecting and non-reflecting micro points. We can write the data once and read any number of times but the data written cannot be either copied or erased and rewritten and hence the name. For copies each disc has to be written burning the chemical coating. This technique we use to record functions such as marriages, etc.,



CD R/W

In this type of CD we can write the data, read and rewrite after erasure. For this two different materials / phenomena via phase change materials and magneto-optic materials are used in general.

Digital Versatile Disc (DVD)

In 1996, a new read only optical system called digital versatile disc with enough capacity (4.7GB) to hold 130 minutes of compressed video, or more than 90% of all feature-length movies using laser of shorter wavelength and focusing lens of larger numerical aperture is introduced. Then DVD R/W also introduced.

Digital Video Recording (DVR)

With this system, 22GB can be recorded on a single layer of 12cm disc. The most important commercial application of this system is recording of high definition digital video. By reducing the spot size using a laser of shorter wavelength and objective lens of higher numerical aperture a real density is increased.

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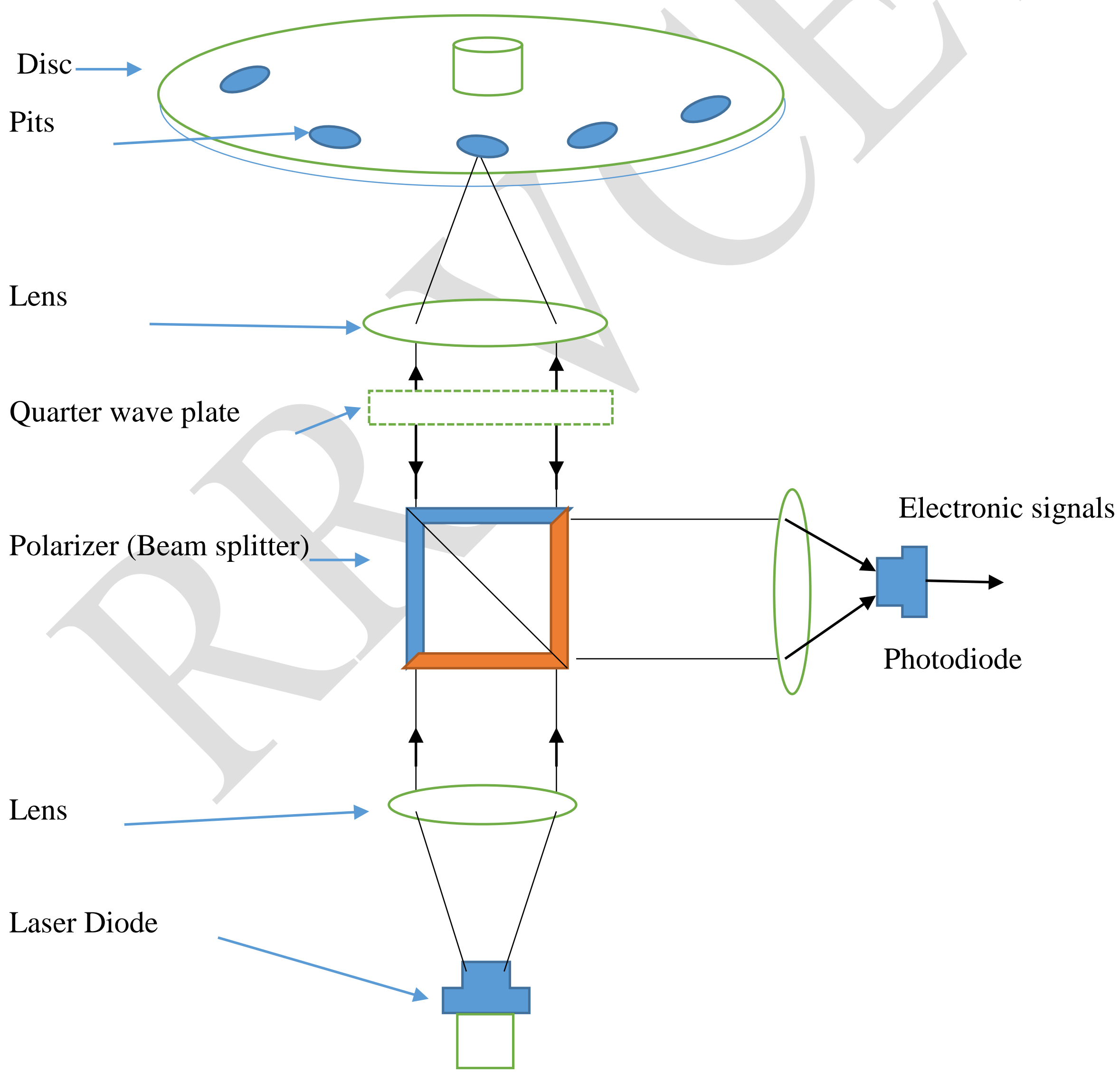
Advantages of optical disc

The optical discs have several advantages over semiconductor memories. Some of these include their larger data storage capacity, shorter access time size. Therefore they are used in terminal equipment of computers as well as in audio visual equipment.

Read only optical discs equipment

CD's which are 120mm in diameter are typical digital audio discs. Compact discs usually means digital audio compact discs, but it is also includes the read only memory (CD –ROM) for data memory and interactive compact disc (CD- I) for multimedia use. Audio information (sound) is digitally recorded in stereo on the surface of a CD in the form of microscope "pits" and flats". The light emitted from the laser diode passes through the lens and it is focussed to a diameter of about 1mm on the surface of a disk. As the CD rotates, the lens and beam follow the track under control of a servo motor. The laser light which is altered by the pits and flats along the recorded track is reflected back from the track through the lens and optical system to infrared photodiodes. The signal from the photodiodes is then use to reproduce the digitally recorded sound.



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5. Nano Devices

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Part – A

1. **Define nano materials**
   Nano phase materials are newly developed materials with grain size at the nanometre range (10^{-9}) in the order of 1 - 100 nm.
2. **Define density of energy states**
   Density of energy is define as the number of available energy states per unit volume per unit energy in a solid.
3. **What is quantum structure?**
   When a bulk material is reduced in its size, atleast one of its dimension, in order of few nanometres, then the structure is known as quantum structure.
4. **What is quantum confinement?**
   The effect is achieved by reducing the volume of a solid so that the energy levels within it becomes discrete is called quantum confinement.
5. **Define coulomb blockade effect**
   The charging effect which blocks the injection or rejection of a single charge into or from a quantum dot is called Coulomb blockade effect.
6. **What is single electron phenomena?**
   The phenomena of keeping single electron or quantum dot in isolation without tunnelling
7. **What is single electron transistor?**
   A transistor made from a quantum dot that controls the current from source to drain one electron at a time is called single electron transistor.
8. **What is single electron tunnelling?**
   The quantization of charge can dominate and tunnelling of single electron across leaky capacitors carriers the current. This is called single electron tunnelling.
9. **What are quantum dot lasers?**
   A quantum dot laser is a semiconductor laser that uses quantum dots as the active medium in its light emitting region
10. **What are the advantages of quantum dot lasers?**
    (i) Broad spectrum with a specific Wavelength of light emission can be obtained by changing dot size.
    (ii) Because of very small active volume, only very less population inversion is necessary for lasing.
11. **What is a carbon nano tube?**
    The carbon nano tubes are the wires of pure carbon with rolled sheets of graphite like a soda straw
12. **What are the types of carbon nano tube structure?**
    (1) Armchair structure (ii) Zig- zag structure (iii) Chiral structure
13. **How carbon nanotubes are classified?**
    Based on number of layers, the carbon nanotubes are classified as
    (i) Single walled carbon nano tubes (SWCNT) (ii) Multi walled carbon nanotubes (MWCNT). In MWCNT, more than one CNTs are coaxially arranged.
14. **What is meant by Tunnelling?**
    The phenomenon in which a particle, like an electron, encounters an energy barrier in an electronic structure and suddenly penetrates is known as tunnelling.
15. **Define quantum well, quantum wire and quantum dot**

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An electrically isolated region, like a thin film, where electrons are constrained in one dimension and exhibiting quantum behaviour is called quantum well

An electrically isolate region, like a nanotube or nano wire, where electrons constrained in two dimensions and exhibiting quantum behaviour is called quantum wire

An electrically isolated region, such as a particle or a portion of a bulk semiconductor, where electrons are constrained in all three directions, creating an artificial atom that exhibit quantum behaviour is called quantum dot.

16. What is meant by Ballistic transport?

When the mean free path of the electron is longer than the dimension of the medium through which the electron travels is called Ballistic transport.

Condition: $L << L_m$

17. Define quantum conductance

The quantum conductance 'G_0' is the quantized unit of electrical conductance

$$G_0 = \frac{2e^2}{h} = 7.7748 \times 10^{-5} mho$$

18. Define quantum resistance

The reciprocal of quantum conductance is called quantum resistance (R_0)

$$R_0 = \frac{1}{G_0} = \frac{h}{2e^2} = 12.9 kohm$$

19. What are the disadvantages of quantum dot laser?

(i) It is very difficult to form high quality dots (uniform size and higher density)

(ii) Difficult to manufacture because of nano meter size

20. Explain the rules which used for the single electron phenomena?

(i) The energy needed to add one electron to the dot, or charging energy E_C must be significantly higher than the thermal energy of an electron $E_c = \frac{e^2}{2C_{dot}} >> K_B T$

(ii) The uncertainity of the charging energy must be less than the charging energy itself.

$$R_t >> \frac{h}{e^2}$$

21. Write down any two applications of carbon nano tube.

(i) It is used to make a computer switching device

(ii) It is used in battery technology in which lithium (charge carriers) can be stored inside nanotube.

(iii) It is used for storing hydrogen which is used in the development of fuel cells

(iv) It can be used to increase the tensile strength of steel

(v) Plastic composite CNT provides shielding from electromagnetic radiation.

(vi) It acts as catalysts for some chemical reactions.

22. What are the applications of quantum dot laser?

(i) QD laser are used in medicine (optical coherence tomography)

(ii) QD lasers are used in display technologies, spectroscopy and telecommunications. Q lasers are used in optical transmission system a LANs.

23. What will happen when the volume is reduce from that of solid to a nano material? (or) what is quantum size effect?

If we decrease the size of the particle to nano size smaller than de Broglie wavelength, the decrease in confining size creates the energy levels discrete. The formation of discrete

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energy levels widens the band gap and finally the band gap energy also increases. Quantum size effect is most significant for nanoparticle semiconductor.

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24. How the density of the states is proportional in 1D, 2D and 3D?

In 1D, D(E) α $E^{-1/2}$

In 2D, D(E) α E

In 3D, D(E) α $E^{1/2}$

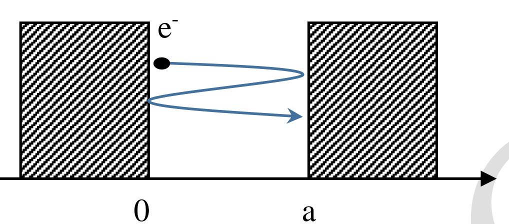
25. What is quantum structure?

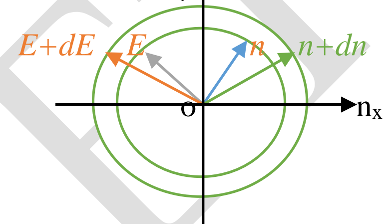
When a bulk material is reduced in its size, atleast one of its dimension, in the order of few nanometres, then the structure is known as quantum structure.

Part – B

1. Discuss density of states in quantum well, quantum wire and quantum dot structure.

The quantum well can be displayed with dimensions of length a, where the electrons of effective mass are confined in the well as shown in fig.





The two dimensional density of states is the number of states per unit area and unit energy. Consider the electron in a two dimensional bounded region of space. We want to find how many quantum states lie within a particular energy, say, between E and E+dE as shown in Figure.

The reduced phase space now consists only the x- y plane and n_x and n_y coordinates.

In 2D space, $n^2 = n_x^2 + n_y^2$

Derivation

The number of available states within a circle of radius '*n*' is given by $\frac{1}{4}\pi n^2$

Here only one quarter of circle will have positive integer values

The number of states within a circle of radius *n*+*dn* is given by $\frac{1}{4}\pi(n+dn)^2$

The number of available energy states lying in an energy interval *E* and *E*+*dE*

$$Z'(E)dE = \frac{1}{4}\pi\left[(n+dn)^2 - n^2\right]$$

$$= \frac{\pi}{4}\left[n^2 + dn^2 + 2ndn - n^2\right]$$

As dn^2 is very small, we can neglect dn^2. Therefore we get,

$$Z'(E)dE = \frac{\pi}{4}[2ndn] = \frac{\pi}{2}ndn \quad (1)$$

We know that $n^2 = \frac{8m^*E}{h^2}a^2$ (2)

(or) $n = \left[\frac{8m^*E}{h^2}\right]^{1/2} a$ (3)

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(or) $dn = \left[\frac{8m^*}{h^2}\right]^{1/2} a\frac{1}{2}E^{-1/2}dE$ (4)

Substitute the value of equation (3) and (4) in equation (1), we get

$$Z'(E)dE = \frac{\pi}{2}\left[\frac{8m^*E}{h^2}\right]^{1/2} a\left[\frac{8m^*}{h^2}\right]^{1/2} a\frac{1}{2}E^{-1/2}dE$$

m* is the effective mass in the quantum well

$$Z'(E)dE = \frac{\pi}{4}\left[\frac{8m^*}{h^2}\right]a^2dE \quad (5)$$

Put $a^2 = A$ area of circle

According to Pauli's exclusion principle each energy level can occupy two electrons of opposite spin

i.e., $Z'(E)dE = 2\times\frac{\pi}{4}\left[\frac{8m^*}{h^2}\right]AdE$

Number of quantum states per unit area and unit energy is

$$\frac{Z'(E)dE}{AdE} = 2\times\frac{\pi}{4}\left[\frac{8m^*}{h^2}\right]$$

$Z'(E) = \frac{\pi}{2}\left[\frac{8m^*}{h^2}\right]$ (or) $Z'(E) = \frac{\pi}{2}\left[\frac{8m^*}{(2\pi\hbar)^2}\right]$ [since $h^2 = 4\pi\hbar^2$] (6)

The density of states in two dimensional is given by $Z'(E)^{2D} = \frac{m^*}{\pi\hbar^2}$ for $E >= E_0$ (7)

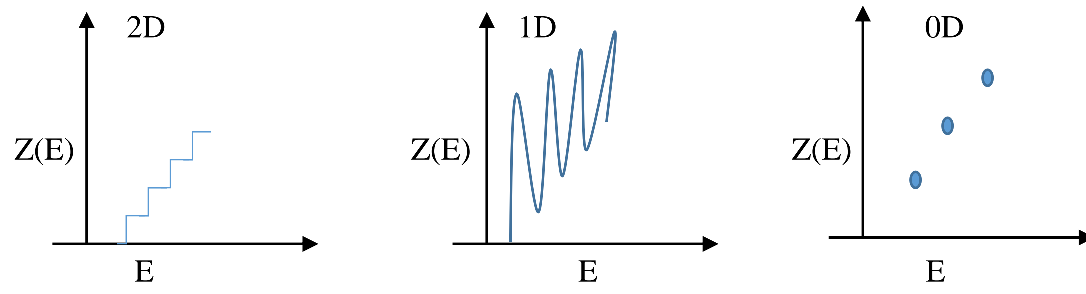
Where E_0 is the ground state of quantum well

$$Z'(E)^{2D} = \frac{m^*}{\pi\hbar^2}\sum_n \sigma(E-E_n) \quad (8)$$

Where E_n are the energies of quantized states and $\sigma(E-E_n)$ is step function.

From equation (7), the density of states in two dimension is constant with respect to the energy.

i.e., $Z'(E)^{2D} \propto E^0 =$ constant



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Density of states in quantum wire

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Consider the one dimensional system, the quantum wire in which only one direction of motion is allowed. (eg. Along x – direction).

In one dimension, such as for a quantum wire, the density of states is defined as the number of available states per unit length per unit energy around an energy *E*. The electron inside the wire are confined in a one dimensional infinite potential well with zero potential inside the wire and infinite potential outside the wire.

At $x = 0$; $V(x) = 0$ for an electron inside the wire

At $x = a$; $V(x) = \alpha$ for an electron outside the wire

The reduced phase space now consists only the x plane and n_x coordinates are shown in figure.

In one dimensional space $n^2 = n_x^2$

The number of available energy states lying in an interval of length is

$$Z'(E)dE = n + dn - n = dn \quad (1)$$

Substitute the value of *dn* from equation (4), we get

$$Z'(E)dE = \left[\frac{8m^*}{h^2}\right]^{1/2} a\frac{1}{2}E^{-1/2}dE \quad (2)$$

According to Pauli's exclusion principle, two electrons of opposite spin can occupy each energy state.

$$Z'(E)dE = 2\times\left[\frac{8m^*}{h^2}\right]^{1/2} a\frac{1}{2}E^{-1/2}dE$$

Number of quantum states per unit length and unit energy is $\frac{Z'(E)dE}{adE} = \left[\frac{8m^*}{h^2}\right]^{1/2} E^{-1/2}$

(or) $Z'(E) = \left[\frac{8m^*}{4\pi^2\hbar^2}\right]^{1/2} E^{-1/2}$ = $Z'(E)^{1D} = \left[\frac{2m^{*1/2}}{\pi\hbar}\right]E^{-1/2}$ (3)

If the electron has potential energy E_0 we have $Z(E)^{1D} = \frac{1}{\pi\hbar}\sqrt{\frac{2m^*}{(E-E_0)}}(E \geq E_0)$ (4)

From equation (4) the density of states in one dimensional system has a functional dependence on energy $Z(E)^{1D} \alpha E^{-1/2}$

For more than one quantized state, the one dimensional density of states is given by

$$Z(E)^{1D} = \frac{1}{\pi\hbar}\sum\sqrt{\frac{2m^*}{(E-E_0)}}\sigma(E-E_n) \quad (5)$$

Where E_n are the energies of the quantized states of the wire and $\sigma(E-E_n)$ is the step function. The density of states in quasi-continuum (or) quantum wire is shown in figure. The discontinuities in the density of states are known as **Van Hove Singularities**

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Density of states in Quantum dot

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In a zero dimensional system, the density of states are truly discrete and they don't form a quasi continum.

In zero dimensional system (quantum dot), the electron is confined in all three spatial dimensions and hence to motion of electron is possible. Each quantum state of a zero dimensional system can therefore be occupied by only two electrons. So the density of states for a quantum dot is merely a delta function.

$$Z(E)^{0D} = 2\sqrt{(E - E_0)} \qquad (6)$$

Here, the factor 2 accounts for spin. For more than one quantum state, the density of states is given by $Z(E)^{0D} = \sum_n 2\delta\sqrt{(E - E_0)}$

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2. Describe the carbon nano tubes with their properties and applications

The hexagonal lattice of carbon is simply graphite. A single layer of graphite is called graphene. CNT consists of a graphene layer rolled up into a cylindrical shape like a single molecule where each molecule nanotube is made up of a hexagonal network of covalently bonded carbon atoms Eg: fullerene. In some cases, the hexagon are arranged in a spiral form, the layer appears like a net having a large hexagonal mesh. The carbon nanotubes are hollow cylinders of extremely thin diameter, 10,000 times smaller than a human hair.

Structures of CNT

The CNTs have many structures on the basis of their length, type of spiral and number of layers. Their electrical properties depend on their structure and they act as either a metal or a semiconductor.

Types of CNT:

(i) Arm chair
(ii) Zigzag
(iii) Chiral

- The axis of tube parallel to c-c bonds of the carbon hexagons are arm chair
- The axis of the tube is perpendicular to c-c are zigzag structure
- The axis of tube is inclined to c-c are chiral structure

Classification:

(i) Single walled CNTs
(ii) Multi walled CNTs

in Multiwalled CNTs more than one CNTs are coaxially arranged

Properties:

Electrical:

(i) CNTs are metallic (or) semi conducting depending on diameter of chirality

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(ii) The energy gap of semiconducting chiral carbon nanotubes is inversely proportional to the diameter of tube.

(iii) The energy gap also varies along the tube axis and reaches a minimum value at the tube ends. This is due to the presence of localised defects at the ends due to the extra energy states.

(iv) In SWCNT conduction occurs through discrete electronic states that are coherent between the electrical contacts.

Mechanical:

(i) The strength of C – C bond is very high leading to ultimate tensile strength

(ii) Young's modules is 5 times greater than steel.

(iii) Tensile strength is 50 times higher than steel

(iv) Carbon nanotubes have ability to withstand extreme strength

(v) It can recover from severe structural distortions due to rehybridization

(vi) The strength of sp^2 C-C bond gives high hardness for CNTs

Physical

(i) It have a high strength to weight ratio. This is indeed useful for light weight applications. (SWCNT $\rightarrow \rho = 0.8$ g/cm^3; MWCNT $\rightarrow \rho = 1.8$ g/cm^3).

(ii) The surface are of nanotubes is of the order of 10-20 m^2/g which is higher than that of graphite.

Chemical

(1) They are highly resistant to any chemical reaction.it is difficult to oxidize them and the on set of oxidation in nanotubes is 100° C higher than that of carbon fibres.

Thermal

Nanotubes have a high thermal conductivity and the value increase with decrease in diameter

Applications:

(i) It is used in development of flat panel displays

(ii) It is used to design LEDs, FET and as switching devices

(iii) It is used to produce battery, solar and fuel cells

(iv) It is used as sensitive detector of various gases.

(v) It is used as a catalyst for chemical reactions.

(vi) It provides light weight shielding material for electromagnetic radiation

(vii) It is used in nano scale electronic devices

(viii) CNTs are used in drug delivery

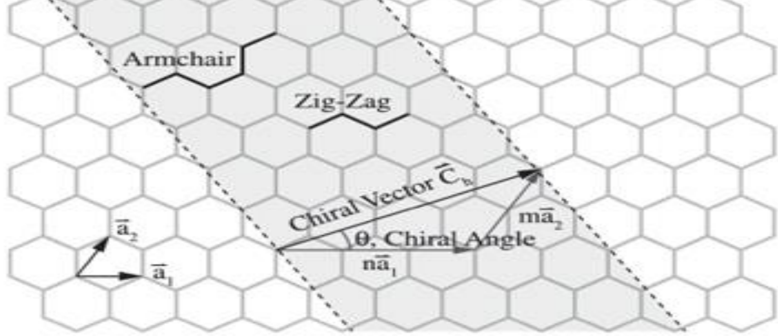

Figure 1. Schematic representation of rolling graphene layer to create CNT[15].

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3. Explain the electron density in bulk material and size dependent of fermi energy

The bulk material is a collection of atoms having properties that are from individual atoms. The nanomaterials gives unique electronic properties.one of the mayor difference in nanomaterials with respect to bulk materials is the number of available energy states. In a bulk material, the states within each energy sublevel are so close that they blend into a band.

The total number of electron states N with energies up to E, can be determined based on the equation $N = \frac{\pi}{3}\left[\frac{8m}{h^2}\right]^{3/2} E^{3/2}.V$ (1)

Here, we represent the volume as *V*, *m* is the mass of an electron an *h* is the Planck's constant.

The number of energy states per unit volume is given by $n = \frac{N}{V} = \frac{\pi}{3} \times \left[\frac{8m}{h^2}\right]^{3/2} E^{3/2}$ (2)

Density of states is defined as number of available electron energy states per unit volume, per unit energy i.e., Z(E) = dn / dE (3)

Hence equation (2) becomes,

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

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

From equation (4), the density of states for a bulk material is directly proportional to square root of energy

i.e., Z(E) α √E (5)

The relevant application of density of states is that it provides information about nanomaterials.

Here, the fermi function gives the probability of occupation by the free electrons in a given energy state.

i.e., $f(E) = \frac{1}{1 + e^{\frac{E - E_f}{kT}}}$ (6)

Then, the number of free electrons per unit volume is $n_e = \int_0^{\alpha} F(E)Z(E)dE$

Put F(E) = 1 at T = 0K, then $n_e = \frac{\pi}{2} \times \left(\frac{8m}{h^2}\right)^{3/2} \int_0^{\alpha} E^{1/2} dE$

(or) $n_e = \frac{\pi}{3} \times \left(\frac{8m}{h^2}\right)^{3/2} E_f(0)^{3/2}$ (7)

Size dependence of Fermi energy

In terms of the distribution of energy, solid have thick energy bands, whereas atoms have thin, discrete energy states. Hence to make a solid behave electronically more like an atom, we need to make it about the same size as an atom.

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Hence rearranging equation (7) , we get $E_f(0) = \frac{h^2}{8m} \times \left(\frac{3n_e}{\pi}\right)^{2/3}$ (8)

In the above equation, 'n' is the only variable.

Equation (8) suggests that the fermi energy of a conductor depends on the number of free electrons 'N' per unit volume 'V' $E_F(0) \alpha (n)^{2/3} \alpha \left(\frac{N}{V}\right)^{2/3}$ (9)

Since the electron density is a property of the material, the fermi energy does not vary with material's size. E_F is same for a particle or for a brick of copper. Hence the energy state will have the same range for small volume and large volume of atoms. But for small volume of atoms we get larger spacing between states. This is applicable to semiconductors and insulators.

Let us consider that all states up to $E_F(0)$ are occupied by a total of free electrons (N).

$$\Delta E = \frac{E_F(0)}{N} \quad (10)$$

From equation (9) & (10), $\Delta E \alpha \frac{1}{V}$ (11)

Thus, the spacing between energy states is inversely proportional to the volume of the solid. The energy sublevel and the spacing between energy states within it will depend on the number of atoms as shown in figure. At one point, we know that an energy sublevel must be divided as many times as there are atoms in a solid, which eventually results too many splits to differentiate. Hence, we just refer to each sublevel as a solid energy band. On the other hand, a single atom in the sublevel contain only one discrete energy state. If we reduce the volume of s solid, the tiny piece of material behaves electronically like an artificial atom.

4. Discuss quantum size effect and band structure of nano crystals.

When the size of a nanocrystal becomes smaller than the deBroglie wavelength, electrons an holes gets spatially confined, electrical dipoles gets generated, the discrete energy levels are formed. As the size of the material decreases, the energy separation between adjacent levels increases. The density of states of nanocrystals is positioned in between discrete (as that of atoms and molecules) and continuous (as in crystals).

Quantum size effect is most significant for semiconductor nanoparticles. In semiconductors, the bandgap energy is of the order of few electron volts and increases with a decrease in particle size.

When photons of light fall in a semiconductor, only those photons with energy are absorbed and a sudden rise in absorption is observed when the photon energy is equal to the bandgap.

As the size of the particle decreases, absorption shifts towards the shorter wavelength (blue shifts) indicating an increase in the bandgap energy .A change in absorption causes a change in the colour of the semiconductor nanoparticle.

For example, bulk cadmium sulphide is orange in colour and has a bandgap of $2.42eV$. It becomes yellow and then ultimately white as its particle size decreases and the bandgap increases.

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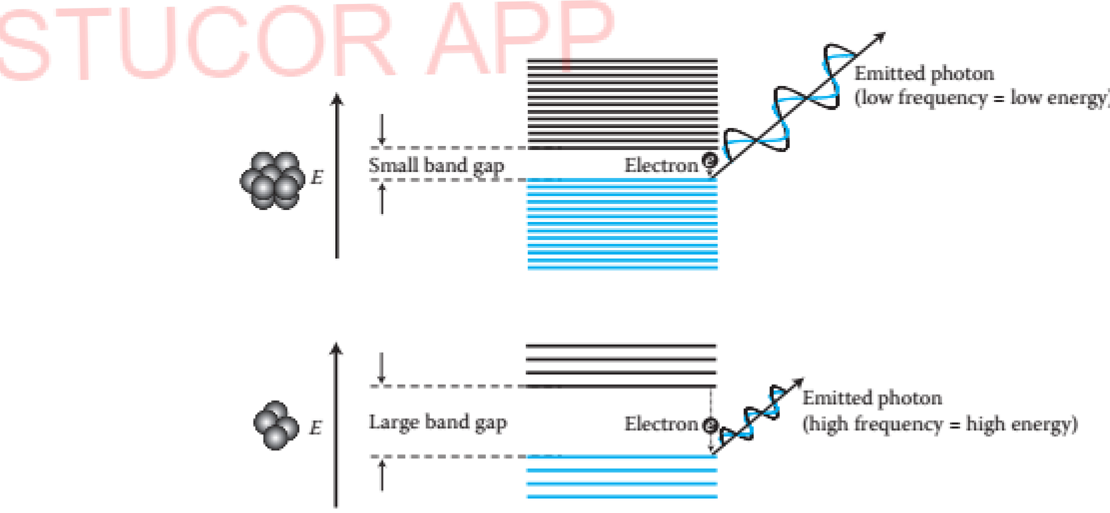

5. Explain the single electron phenomena and Describe the construction and working of single electron transistor

Single electron phenomena

Transistors are what computers used to compute-tiny switches turning on and off, transferring and amplifying signals, making logic decisions. Today, microchips have over a billion transistors, each one turning on and off a billion times every second. These chips require manufacturing processes with roughly 100-nm resolution. And every year this resolution drops, enabling even smaller transistors, so that even more of them can be squeezed into the same amount of space. Rather than moving torrents of electrons through transistors, it may very well be practical and necessary to move electrons *one at a time*. We can use transistors to make sensitive amplifiers, electrometers, switches, oscillators, and other digital electronic circuits all of which operate using single electrons

Rules for single electron phenomena to occur

Tunnelling is the way electrons cross both the physical barriers and the energy barriers separating a quantum dot from the bulk material that surrounds it. If any electron on one side of the barrier could just tunnel across it, there would not be any isolation. The dot would not be a quantum dot because it would still essentially be part of the bulk.

So we need to be able to control the addition and subtraction of electrons. We can do this with voltage biases that force the electrons around. There are two rules for preventing electrons from tunnelling back and forth from a quantum dot.

(i) Coulomb blockade effect
(ii) Overcoming uncertainity

Rule1: Coulomb Blockade effect

A quantum dot has a capacitance, C_{dot}, a measure of how much electric charge it can store

$$C_{dot} = G\, \varepsilon\, d \qquad (1)$$

Here, ε is the permittivity of the material surrounding the dot, *d* is the diameter of the dot, and *G* is a geometrical term (if the quantum dot is a disk, *G* = 4; if it is a spherical particle,

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G = 2π). An object isolated in space can store charge on its own and therefore can have a capacitance.

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The energy needed to add one negatively charged electron to the dot is known as the charging energy, $E_C = \frac{e^2}{2C_{dot}}$ (2)

We know that the coulomb blockade can prevent unwanted tunnelling. Hence we can keep the quantum dot isolated, the condition for this is given by $E_C \gg K_B T$ (3)

Rule2: Overcoming uncertainity

The uncertainty in the energy of a system is inversely proportional to how much time we have to measure it. Specifically, the energy uncertainty, ΔE, adheres to this relationship

$$\Delta E \approx \frac{h}{\Delta t} \quad (4)$$

Here, h is Planck's constant and Δt is the measurement time. Since it is a tiny capacitor, the time we use for Δt is the capacitor's time constant (the characteristic time a capacitor takes to acquire most of its charge). The time constant of a capacitor is RC, where R is the resistance and C is the capacitance. In our case, the resistance is the tunnelling resistance, R_t, and the capacitance is C_{dot}. This gives us $\Delta t = R_t C_{dot}$ (5)

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Our goal is to keep electrons from tunnelling freely back and forth to and from the dot. To ensure this, *the uncertainty of the charging energy must be less than the charging energy itself*.

For maintaining electron isolation in quantum dot, we need $\Delta E_c < E_c$ (6)

Substituting equation (2), (4) and (5) in (6), we get $\frac{h}{R_t C_{dot}} < \frac{e^2}{2C_{dot}}$ (7)

In otherwords, $R_t \gg \frac{h}{e^2}$ (8)

Meeting this criterion is often as simple as making sure the insulating material surrounding the dot is thick enough. These two rules help in building a single-electron transistor (SET)

Single electron transistor (SET)

Principle

A transistor with three terminal switching device made from a quantum dot that controls the current from source to rain one electron at a time is called single electron transistor

Construction

The single electron transistor (SET) is built like a conventional Field Emitting Transistor (FET). It has tunnelling junctions in place of pn – junctions and quantum dot in place of the channel region of the FET. To control tunnelling, a voltage bias to the gate electrode is applied. A separate voltage bias is applied between source and drain electrodes for the current direction. For current to flow, gate bias voltage must be large enough to overcome the coulomb blockade energy.

Working

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1. The purpose of SET is to individually control the tunnelling of electrons into an out of the quantum dot. To do this, we must first stop random tunnelling by choosing the right circuit geometry and materials. If an electron comes or goes from the dot. It will on purpose
2. To control tunnelling, we apply a voltage bias to the gate electrode. There is also a voltage difference between the source and the drain that indicates the direction of current. Here, we can say that current and electron flow in the same direction and we will consider the electrode from which the electrons originate.
3. This is similar to the working of FET, where the gate voltage creates an electric field that alters the conductivity of the semiconducting channel below it, enabling current to flow from source to drain.
4. Applying a voltage to the gate in an SET creates an electric field and change the potential energy of the dot with respect to the source and drain. This gate voltage controlled potential difference can make electrons in the source attracted to the dot and simultaneously electrons in the dot attracted to the drain.
5. For current to flow, this potential difference must be atleast large enough to overcome the energy of the coulomb blockade.

The energy "*E*" needed to move a charge *e* across a potential difference *V* is given by $E=Ve$

So, the voltage that will move an electron onto or off the quantum dot is given by

$$V = \frac{E_c}{e} \quad (or) \quad V = \frac{\frac{e^2}{2C_{dot}}}{e} = \frac{e}{2C_{dot}} \tag{1}$$

With this voltage applied to quantum dot, an electron can tunnel through coulomb blockade of the quantum dot.

Working for single electron transistor in nutshell

A single electron transistor is shown in figure. As opposed to the semiconductor channel in a field effect transistor, the SET has an electrically isolated quantum dot located between the source and drain.

1. The SET is OFF mode. The corresponding potential energy diagram shows that it is not energetically favourable for electrons in the source to tunnel to the dot as shown in figure.
2. The SET is ON mode. At the lowest setting electrons tunnel one at a time, via the dot, from the source to the drain as shown in figure.
3. This is made possible by first applying the proper gate voltage, $V_{gate} = e/2C_{dot}$, so that the potential energy of the dot is made low enough to encourage an electron to tunnel through the coulomb blockade energy barrier to the quantum dot.
4. Once the electron is on it, the dots potential energy rises as shown in figure
5. The electron then tunnels through the coulomb blockade on the other side to reach the lower potential energy at the drain as shown in figure.
6. With the dot empty and the potential lower again the process repeats as shown in figure.

Advantages

1. The fast information transfer velocity between cells is carried out via electrostatic interactions only.

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2. No wire is needed between arrays. The size of each cell can be can be as small as 2.5nm. This made them suitable for high density memory.
3. This can be used for the next generation quantum computer.

Limitations

1. In order to operate SET circuit at room temperature, the size of the quantum dot should be smaller than 10*nm*
2. It is very hard to fabricate by traditional optical lithography and semiconductor processes
3. The method must be developed for connecting the individual structures into logic circuits and these circuits must be arranged into larger 2D patterns.

Applications

1. SET are used in sensor and digital electronic circuits
2. Variety of digital logic functions, including AND or NOR gates, is obtained based on SET operating at room temperature.
3. It is used for mass storage
4. It is used in highly sensitive electrometer.
5. SET can be used as a temperature probe, particularly in the range of very low temperatures.
6. SET is a suitable measurement setup for single electron spectroscopy.
7. It is used for the fabrication of homo-dyn receiver operating at frequencies between 10 and 300 *MHz*

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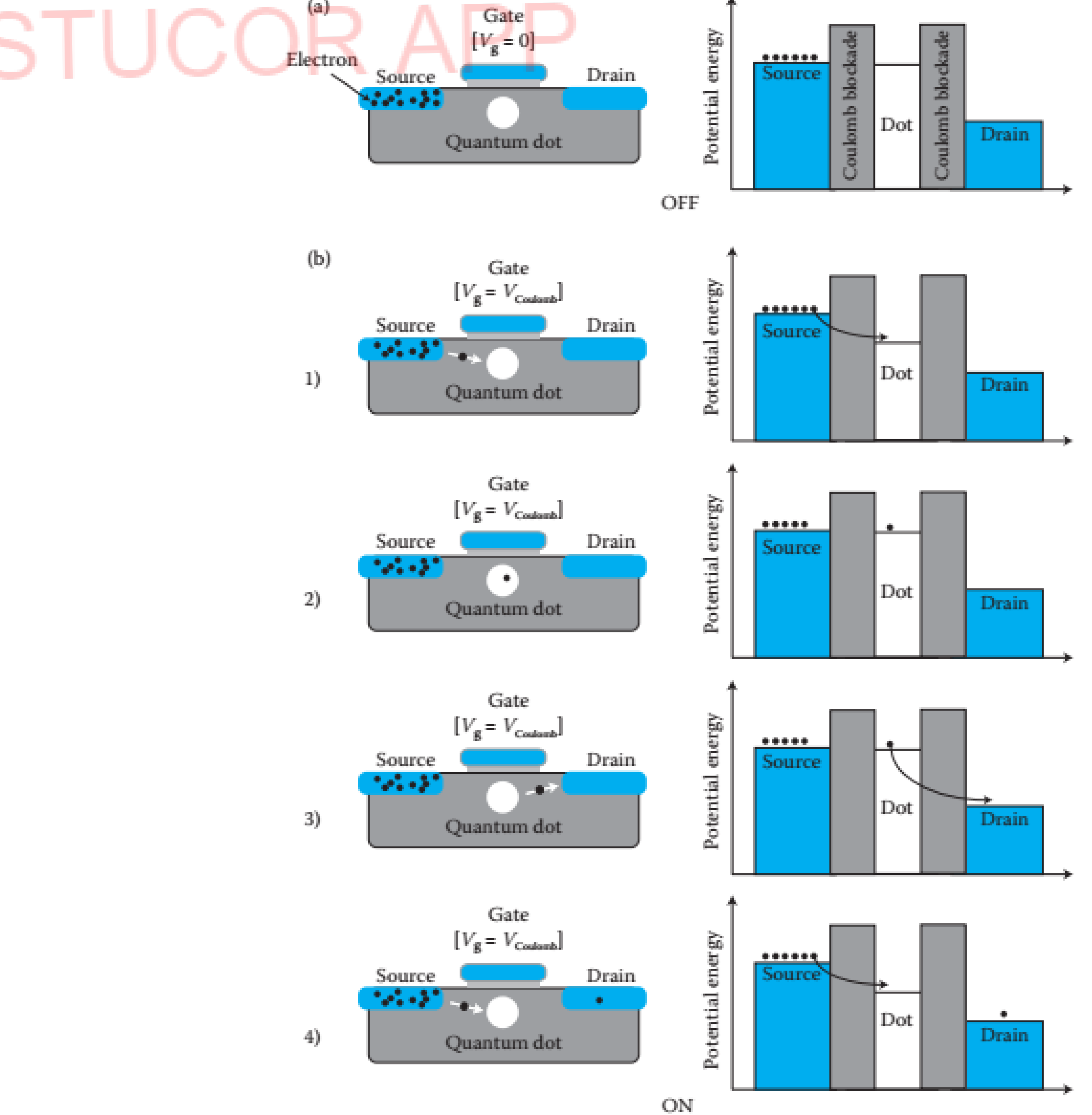

8. Describe principle, construction and working of quantum dot laser.

Principle

A quantum dot laser is a semiconductor laser that uses quantum dots as the active medium in its light emitting region.

Construction

Figure shows a quantum dot near infrared laser diode grown on an *n* doped GaAs substrate. The top *p* metal layer has a GaAs contact layer. Immediately below it there are a pair of 2*μm* thick $Al_{0.85}Ga_{0.15}As$ cladding bounding layers that surrounds a 190 *nm* thick waveguide made of $Al_{0.05}Ga_{0.95}As$ in between *p* metal and *n* substrate. The front view of quantum laser diode is shown in figure. Here the waveguide plays the role of conducting the emitted light to the exit ports at the edges of the structure.

The waveguide is a 30 *nm* thick GaAs region, an centred in this region are 12 monolayers of $In_{0.5}Ga_{0.5}As$ quantum dots with a density of 1.5 X 10^{-10} cm^2. The details of the wavelength region is drawn below

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Working

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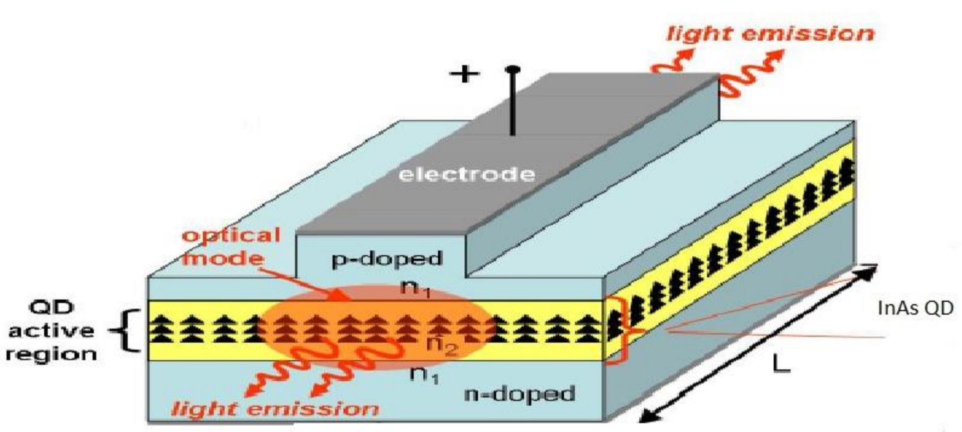
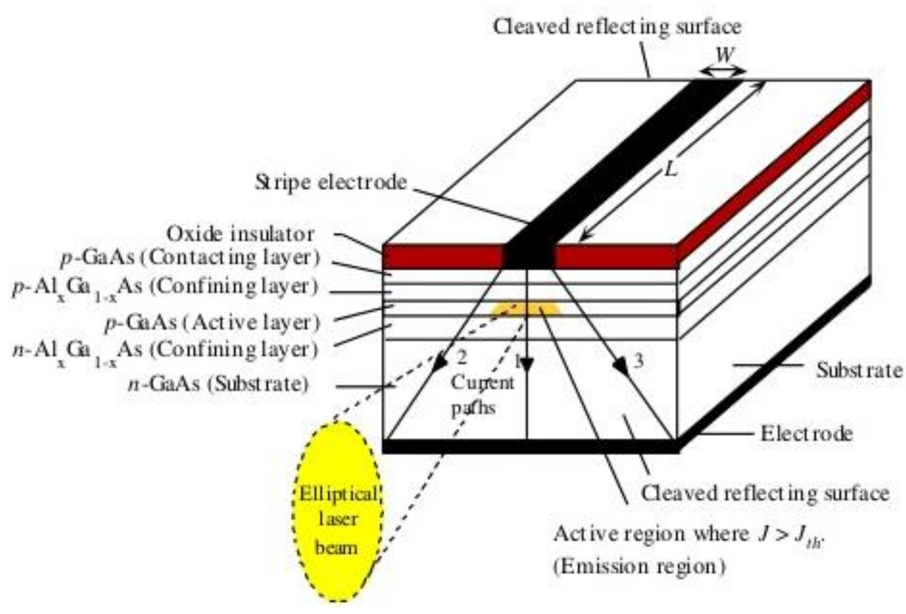
1. The electron and hole recombination causes the emission of laser light.
2. By varying the length L_c and width W the laser light with particular wavelength will be emitted.
3. A particular wavelength of 1.32 μm which is near infrared region can be produced for a current setting just above the 4.1mA threshold value, labelled point a as shown in figure.
4. The faces of the layer were coated with high reflected material where the light is reflected back and forth to increase the stimulated emission and in turn the laser emission is enhanced.





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9. Write short notes on

(i) Ballistic transport (ii) Quantum resistance (iii) quantum conductance

Ballistic transport

Definition

When the mean free path of the electron is longer than the dimension of the medium through which the electron travels is called ballistic transport

Explanation

When the length L of the conductor becomes much smaller than the mean free path L_m the transport is termed *ballistic* meaning that the electrons do not scatter during the time it takes to travel through the conductor.

For example, ballistic transport can be observed in a metal nano wire. This is because the wire is of the size of a nanometer and the mean free path can be longer than in a metal.

Condition for ballistic transport

The mean free path can be increased by reducing the number of impurities in a crystal or by lowering its temperature.

i.e., $L << L_m$ and $L << L_\varphi$

where L length of the conductor, L_m mean free path, L_φ length over which an electron can travel before having an elastic collision. This is also called phase coherence length since it is the length over which an electron wave function retains its coherence. For $L << L_m$ and $L << L_\varphi$, we have ballistic transport. Ballistic transport occurs over very small length scales, and is obviously coherent.

The electron does not hit anything as it travels through the material and therefore there is no momentum or phase relaxation. Thus in ballistic material, the electron wave function can be obtained from schrodinger's equation.

Application

It is used in ultra-short channel semiconducting FETs or carbon nanotube transistors.

Quantum conductance and resistance

The quantum conductance is the quantised unit of electrical conductance denoted by G_o

$$G_0 = \frac{2e^2}{h} = 7.748 \times 10^{-5}\, mho$$

The reciprocal of the quantum conductance is quantum resistance denoted by R_0

$$R_0 = \frac{h}{2e^2} = 12.9\, k\Omega$$

Derivation

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A one dimensional quantum wire connects adiabatically two reservoirs with chemical potential μ_1 and μ_2. The connections are assumed to be non-reflecting.

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Reservoirs with chemical potential μ_1 and μ_2

It is also assumed that the wire is sufficiently narrow so that only the lowest transverse mode in the wire is below the fermi energy (E_F)

The current density is given by $J = -nev_d$ (1)

The density of electrons is determined by $n = \int_{\mu_2}^{\mu_1} dn = \int_{\mu_2}^{\mu_1} \frac{dn}{dE} dE = \frac{dn}{dE} \int_{\mu_2}^{\mu_1} dE$

$$n = \frac{dn}{dE}[\mu_1 - \mu_2] \quad (2)$$

Substituting equation (2) in (1), we get $J = -\frac{dn}{dE}[\mu_1 - \mu_2]eV_d$ (3)

where dn/dE is the density of states.

We know that E = N h ν (4)

Where N is the number of electrons

We know that $n = \frac{N}{V} = \frac{No.of electrons}{volume} = \frac{No.of electrons}{length \times area} = \frac{N}{A \times l}$

Therefore $N = nAl$ (5)

Substituting equation (5) in (4). We get

$E = n\ h\ \nu\ A\ l$

Differentiating we get

$dE = dn\ h\ \nu\ A\ l$

$$\therefore \frac{dn}{dE} = \frac{1}{h\nu Al} \quad (6)$$

According to spin degeneracy, multiply equation (6) by two, we get

$$\frac{dn}{dE} = \frac{2}{h\nu Al} \quad (7)$$

If V is the voltage between two reservoirs, then we can write

$$\mu_1 - \mu_2 = -eV \quad (8)$$

Substituting equation (7) and (8) in equation (3) we get

$$J = \frac{2}{h\nu Al} eVeV_d$$

(or) $\frac{J\nu Al}{V_d} = \frac{2}{h} e^2 V$

(or) $\frac{I\nu Al}{AV_d} = \frac{2}{h} e^2 V \quad = \quad \frac{I\nu l}{V_d} = \frac{2}{h} e^2 V$ (9)

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We know that velocity = distance / time an frequency = 1/ time

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$$\therefore V_d = \frac{l}{t} \qquad (10)$$

and $$\therefore V = \frac{1}{t} \qquad (11)$$

Substitute (10) and (11) in (9), we get

$$\frac{Il}{t(l/t)} = \frac{2}{h}e^2V$$

(or) $$\frac{I}{V} = \frac{2e^2}{h}$$

(or) $$\frac{1}{R_0} = \frac{2e^2}{h} \qquad (12)$$

Therefore equation (13) can also be rewritten as

$$G_0 = \frac{1}{R_0} = \frac{2e^2}{h} \qquad (13)$$

Therefore quantum conductance $G_0 = \frac{1}{R_0} = \frac{2e^2}{h}$ = 7.748 X 10^{-5} siemens (or) mho (14)

And quantum resistance $R_0 = \frac{h}{2e^2} = 12.9k\Omega$ (15)

Here G_0 is a fundamental unit

If there are *N* electronic channels, then equation (14) becomes

$G_0 = \frac{2e^2}{h}N$ called **Landauer** formula (16)

i.e., $G = G_0N$

similarly $R_0 = \frac{h}{2e^2} \times \frac{1}{N} = \frac{R_0}{N}$ (17)

As the number of electronic channels increases, conductance increases and resistance decreases. The classical theory also predicts this behaviour, although the quantum theory shows that this happen in discrete steps, as the number of electron channel increases.

As *N* gets very large, the electron channels essentially form a continum and the quantum theory tends towards the classical limit.

10. Write a short note on conductivity of metallic nano wires.

Consider a circular cross section wire which has a radius *a* and length *L* . Assume that *L* is very large relative to its mean free path.

Let us assume a copper wire having radius a = 10 *mm* , R = 5.395 X 10^{-5} *ohms / meter* and σ =5.9 X 10^7 *S/m.* we need 18357m for 1Ω resistance to be maintained in the given radius of the

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wire. For $a = 10\ \mu m$, $R = 53.05\Omega$ /m amounting to 1 Ω in only 1.85 *cm*. If $a = 10\ nm$ then the resistance is huge.

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Here the radius of the wire having radius on the order of its mean free path or less will have different conductance value compare to the bulk scale. For example, copper has a mean free path of approximately 40 *nm* and hence radius dependence effects usually occurs when the radius is double this value (80 – 100 *nm*).

A 1 -20*nm* radius range, the conductivity values changes from the bulk value and decreases as the radius *a* decreases. This is due to scattering effect from the wire surface, grain boundaries, defect free metals at small scales.

A relatively simple approximation for the resistivity of rectangular cross section of wires is

$$\rho = \rho_0 \left\{ \frac{1}{3\left[\frac{1}{3} - \frac{\alpha}{2} + \alpha^2 - \alpha^3 \ln\left[1 + \frac{1}{\alpha}\right]\right]} + \frac{3}{8} C(1-P) \frac{1+AR}{AR} \times \frac{L_m}{W} \right\} \quad (1)$$

Where $\alpha = \frac{L_m}{d} \times \frac{R_c}{1-R_c}$

Where ρ_0 – bulk resistivity

W – wire width

AR – aspect ratio (wire height / wire width)

d – average grain size

P – specularity parameter

R_c – grain boundary reflection coefficient

C – constant

Here the first term is related to grain boundary scattering and the second term wire surface scattering. Both P and R_C can take values between 0 and 1. The experimental results are P = 0.3 - 0.5 and R_c = 0.2 - 0.3.

The proceeding model may work down to wire cross sectional dimensions on the order of 5 – 10 nanometres. Below which a quantum wire model that accounts for transverse quantization would be necessary. However as complicated as surface and grain boundary scattering are, other factors also determine the conductivity of nanowire

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