

# **LECTURE NOTES**

# **ON**

# **APPLIED PHYSICS**

## **B.TECH I YEAR- I SEMESTER**

## **(R19)**



**DEPARTMENT OF HUMANITIES & SCIENCES**

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# UNIT-1

## Wave Optics

### Introduction

Optics is the branch of physics which includes the study of light and the phenomena associated with its generation, transmission and detection. Light is visible portion of the electromagnetic spectrum. Its properties are classified into three categories as follows.

- (1) Geometrical optics
  - (i) Reflection
  - (ii) Refraction
  - (iii) Dispersion
- (2) Physical optics
  - (i) Interference
  - (ii) Diffraction
  - (iii) Polarization
- (3) Quantum optics
  - (i) Lasers
  - (ii) Non-linear effects

Geometrical optics assumes that light travels in straight lines and is concerned with the laws controlling the reflection, refraction, and dispersion of rays of light where as physical optics deals with phenomena that depend on the wave nature of light. Quantum optics considers light as made up of tiny bundles of energy called photons.

### Interference

One of the best phenomena that provide direct evidence for the wave nature of light is interference. Thomas young demonstrated the concept of interference of light in 1802 itself. Examples are the multiple colours on soap bubbles as well as on floating oil film when viewed under sun light. Interference is based on the principle of **superposition of waves**.

Interference can be defined as the superposition of two or more coherent waves with each other such that the intensity modifies maxima and minima which results in a new wave pattern.

#### Constructive interference

If two waves are in phase with the amplitudes  $A_1$  and  $A_2$  and superpose with each other then the crest of one wave will coincide with the crest of the other wave and the amplitude reaches to a maximum. The resultant wave will have amplitude is  $A = A_1 + A_2$ .

The condition for constructive interference is the path difference should be equal to  $n\lambda$ .

$$\text{i.e., } \Delta = n\lambda; n = 0, \pm 1, \pm 2, \dots$$

#### Destructive interference

If two waves are out of phase with the amplitudes  $A_1$  and  $A_2$  and superpose with each other then the crest of one wave will coincide with the trough of the other wave and so will tend to cancel out. The resultant wave will have amplitude is  $A = |A_1 - A_2|$ .

The condition for destructive interference is the path difference should be equal to odd multiples of  $\lambda/2$ .

$$\text{i.e., } \Delta = (2n+1)\lambda/2; n = 0, \pm 1, \pm 2, \dots$$

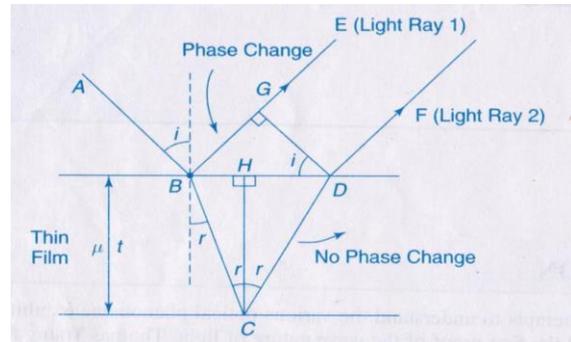
### Conditions for Interference

1. The two light sources emitting light waves should be coherent.
2. The two sources must emit continuous light waves of same wavelength and frequency.
3. The separation between the two sources should be small.
4. The distance between the two sources and the screen should be large.
5. To view interference fringes, the background should be large.
6. The amplitudes of the light waves should be equal or nearly equal.
7. The sources should be narrow.
8. The sources should be monochromatic.

### Interference in thin film by reflection

When light is incident on a plane parallel thin film, some portion gets reflected from the upper surface and the remaining portion is transmitted into the film. Again, some portion of the transmitted light is reflected back into the film by the lower surface and emerges through the upper surface. These reflected light beams superimpose with each other, producing interference and forming interference patterns.

Consider a transparent plane parallel thin film of thickness 't' with refractive index  $\mu$ . Let a monochromatic light ray AB be incident at an angle of incidence of 'i' on the upper surface of the film. BE and BC are the reflected and transmitted light rays. Let the angle of refraction is 'r'. The ray BC will be reflected into the film and emerge through the film in the form of the light ray DF. These two light rays superimpose and depending upon path difference between them, they produce interference patterns.



To know the path difference, let us draw the normal DG and BE. From the points D and G onwards, the light rays travel equal distances. By the time the light ray travels from B to G, the transmitted light ray has to travel from B to C and C to D.

The path difference between light rays (1) & (2) is

$$\text{Path difference} = \mu(BC+CD) \text{ in film} - BG \text{ in air} \quad \text{-----} \rightarrow (1)$$

$$\text{Consider the } \triangle BCH, \cos r = \frac{HC}{BC}$$

$$BC = \frac{HC}{\cos r} = \frac{t}{\cos r}$$

$$\text{Similarly, from } \triangle DCH, CD = \frac{t}{\cos r}$$

To calculate BG, first BD which is equal to (BH+HD) has to be determined.

$$\text{From } \triangle BHC, \tan r = \frac{BH}{CH} = \frac{BH}{t}$$

$$BH = t \tan r$$

$$\text{Similarly, } HD = t \tan r$$

$$\therefore BD = BH + HD = 2t \tan r$$

From  $\triangle BGD$ ,  $\sin i = \frac{BG}{BD}$

$$\begin{aligned}BG &= BD \sin i \\ &= 2t \tan r \sin i\end{aligned}$$

From Snell's law,  $\sin i = \mu \sin r$

$$\therefore BG = 2\mu t \tan r \sin r$$

$\therefore$  From eqn(1), we have

$$\begin{aligned}\text{Path difference} &= \frac{2\mu t}{\cos r} - 2\mu t \tan r \sin r \\ &= 2\mu t \cos r\end{aligned}$$

At the point B, reflection occurs from the upper surface of the thin film. Light ray(1) undergoes an additional phase change of  $\pi$  or an additional path difference of  $\lambda/2$ .

$$\text{Total path difference} = 2\mu t \cos r + \lambda/2$$

When the path difference is equal to integral multiples of  $\lambda$  then the rays (1) & (2) meet in phase and undergoes constructive interference. The condition for bright fringe is  $2\mu t \cos r = (2n-1)\lambda/2$  where  $n = 0,1,2,3,\dots$

When the path difference is equal to half integral multiples of  $\lambda$  then the rays (1) & (2) meet out of phase and undergoes destructive interference. The condition for dark fringe is  $2\mu t \cos r = n\lambda$  where  $n = 0,1,2,3,\dots$

### Newton's ring

Newton's rings are one of the best examples for the interference in a non uniform thin film. When a planoconvex lens with its convex surface is placed on a plane glass plate, an air film of increasing thickness is formed between the two. The thickness of the film at the point of contact is zero. If monochromatic light is allowed to fall normally and the film is viewed in the reflected light, alternate dark and bright rings concentric around the point of contact between the lens and the glass plate are seen. These circular rings were discovered by Newton and are called Newton's ring.

### Experimental arrangement

The planoconvex lens (L) of large radius of curvature is placed with its convex surface on a plane glass plate (P). The lens makes the contact with the plate at 'O'. The monochromatic light falls on a glass plate G held at an angle of  $45^\circ$  with the vertical. The glass plate G reflects normally a part of the incident light towards the air film enclosed by the lens L and the glass plate P. A part of the light is reflected by the curved surface of the lens L and a part is transmitted which is reflected back from the plane surface of the plate. These reflected rays interfere and give rise to an interference pattern in the form of circular rings. These rings are seen near the upper surface of the air film through the microscope.

### Explanation of Newton's ring

A part of the incident monochromatic light AB is reflected at B in the form of the ray (1) with an additional phase (or path) change. The other part of the light is refracted through BC. Then at C, it is again reflected in the form of the ray (2) with additional phase change of  $\pi$  or path change of  $\lambda/2$ .

As the rings are observed in the reflected light, the path difference between them is  $2\mu t \cos r + \lambda/2$ . For air film  $\mu=1$  and for normal incidence  $r=0$ , path difference is  $2t + \lambda/2$ .

At the point of contact  $t=0$ , path difference is  $\lambda/2$ . Then the incident and reflected lights are out of phase and interface destructively. Hence the central spot is dark.

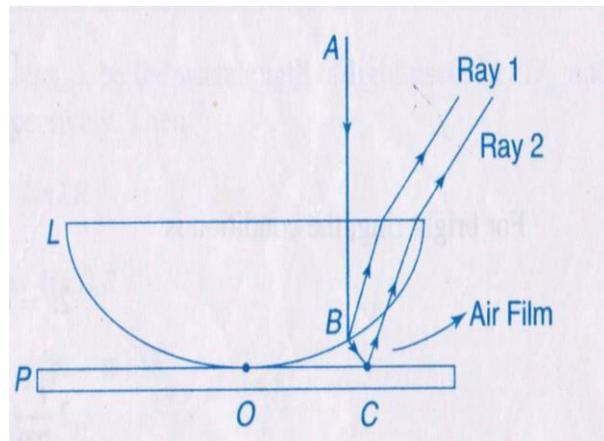
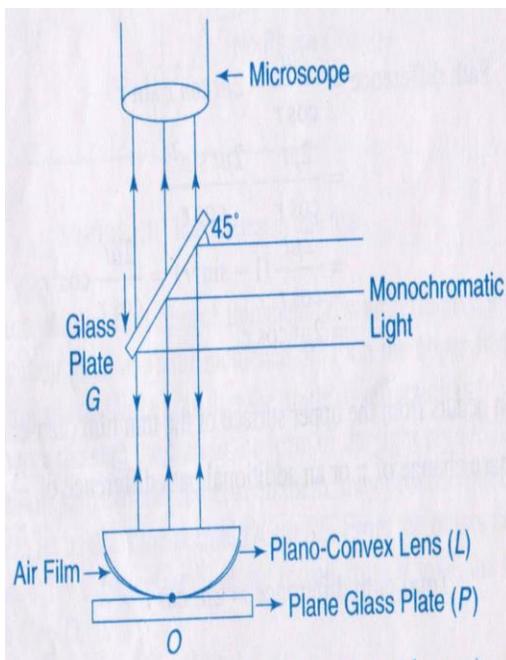
The condition for bright ring is  $2t + \lambda/2 = n\lambda$

$$2t = (2n-1)\lambda/2 ; n = 1,2,3,\dots$$

The condition for dark ring is  $2t + \lambda/2 = (2n+1)\lambda/2$

$$2t = n\lambda ; n = 0,1,2,3,\dots$$

For monochromatic light, the bright and dark rings depends on thickness of the air film. For a Newton's rings system, the focus of points having same thickness lie on a circle having its centre at the point of contact. Thus, we get bright and dark circular rings with the point of contact as the centre.



### Theory of Newton's ring

To find the diameters of dark and bright rings, let 'L' be a lens placed on a glass plate P. The convex surface of the lens is the part of spherical surface with centre at 'C'. Let R be the radius of curvature and r be the radius of Newton's ring corresponding to the film thickness 't'.

From the property of the circle,  $NA \times NB = NO \times ND$

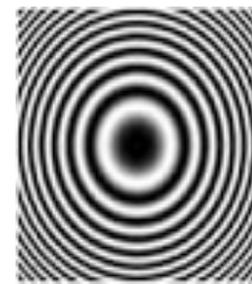
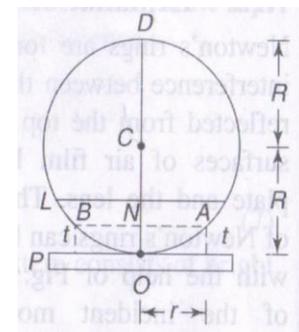
Substituting the value,  $r \times r = t \times (2R-t)$

$$r^2 = 2Rt - t^2$$

As t is small,  $t^2$  will be negligible

$$r^2 = 2Rt$$

$$t = \frac{r^2}{2R}$$



For bright ring, the condition is

$$2t = (2n-1)\lambda/2$$

$$2\left(\frac{r^2}{2R}\right) = (2n-1)\lambda/2$$

$$r^2 = \frac{(2n-1)\lambda R}{2}$$

Replacing r by D/2, the diameter of n<sup>th</sup> bright ring will be

$$\frac{D^2}{4} = \frac{(2n-1)}{2} \lambda R$$

$$D = \sqrt{2n-1} \sqrt{2\lambda R}$$

$$D \propto \sqrt{2n-1}$$

$$D \propto \sqrt{\text{odd natural numbers}}$$

For dark ring, the condition is

$$2t = n\lambda$$

$$2 \frac{r^2}{2R} = n\lambda$$

$$r^2 = n\lambda R$$

$$D^2 = 4n\lambda R$$

$$D \propto \sqrt{n}$$

$$D \propto \sqrt{\text{natural number}}$$

With increase in the order (n), the rings get closer and the fringe width decreases and is shown in fig.

#### Determination of wavelength of a light source

Let R be the radius of curvature of a planoconvex lens,  $\lambda$  be the wavelength of light used. Let  $D_m$  and  $D_n$  are the diameters of m<sup>th</sup> and n<sup>th</sup> dark rings respectively. Then

$$D_m^2 = 4m\lambda R \text{ and } D_n^2 = 4n\lambda R$$

$$D_n^2 - D_m^2 = 4(n-m)\lambda R$$

$$\lambda = \frac{D_n^2 - D_m^2}{4(n-m)R}$$

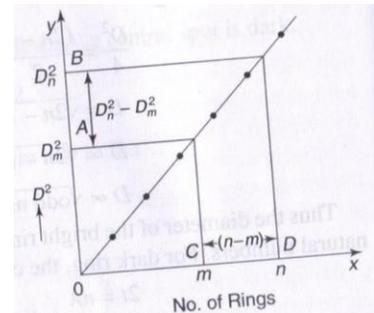
Newton's rings are formed with suitable experimental setup. With the help of a travelling microscope, the readings for different orders of dark rings were noted from one edge of the rings to the other edge. The diameters of different orders of the rings can be known. A plot between  $D^2$  and the no. of rings gives a straight line as shown in fig.

From the graph,

$$\frac{D_n^2 - D_m^2}{(n-m)} = \frac{AB}{CD}$$

The radius R of the planoconvex lens can be obtained with the help of a spherometer. Using these values in the formula,  $\lambda$  can be calculated.

#### Determination of refractive index of a liquid



The experiment is performed when is an air film between the glass plate and the planoconvex lens. The diameters of  $m^{\text{th}}$  and  $n^{\text{th}}$  dark rings are determined with the help of a travelling microscope. We have

$$D_n^2 - D_m^2 = 4(n-m) \lambda R \text{ -----} \rightarrow (1)$$

The system is placed into the container which consists of the liquid whose refractive index ( $\mu$ ) is to determined. Now, the air film is replaced by the liquid film. Again, the diameters of the same  $m^{\text{th}}$  and  $n^{\text{th}}$  dark rings are to be obtained. Then we have

$$D_n'^2 - D_m'^2 = \frac{4(n-m)\lambda R}{\mu} \text{ -----} \rightarrow (2)$$

From (1) & (2), we have

$$\mu = \frac{D_n^2 - D_m^2}{D_n'^2 - D_m'^2}$$

Using the above formula,  $\mu$  can be calculated.

### Diffraction

The phenomenon of bending of light round the corners of obstacles and spreading of light waves into the geometrical shadow region of an obstacle placed in the path of light is called diffraction. The phenomenon of diffraction can be divided into two types.

- 1) Fraunhofer diffraction
- 2) Fresnel diffraction.

#### Fraunhofer diffraction

In this diffraction, the source and screen are placed at infinite distances from the obstacle. Due to the above fact, we need lenses to study the diffraction. This diffraction can be studied in any direction. In this case, the incident wave front is plane.

#### Fresnel diffraction

In this class of diffraction, the source & the screen are placed at finite distances from the obstacle. To study this diffraction, lenses are not necessary as the source & screen are at a finite distance. This diffraction can be studied in the direction of propagation of light. The incident wave fronts are either spherical or cylindrical.

#### Comparison of Fresnel diffraction and Fraunhofer diffraction

Fresnel Diffraction	Fraunhofer Diffraction
1) Either a point source or an illuminated narrow slit is used	1) Extended source at infinite distance is used.
2) The wavefront undergoing diffraction is either spherical or cylindrical.	2) The wavefront undergoing diffraction is a plane wavefront.
3) The source and the screen are finite distances from the obstacle producing diffraction.	3) The source and the screen are at infinite distances from the obstacle producing diffraction.
4) No lens is used to focus the rays.	4) Converging lens is used to focus parallel fringes.

#### Difference between interference and diffraction

Interference	Diffraction
1) Superposition is due to two separate	1) Superposition is due to secondary

<p>wavefronts originating from two coherent waves.</p> <p>2) The fringes normally have equal widths.</p> <p>3) All the bright fringes have the same intensity.</p> <p>4) All the dark fringes have zero intensity.</p>	<p>wavelets originating from different parts of the same wavefront.</p> <p>2) The width between the fringes is never equal.</p> <p>3) The intensity of bright fringes usually decreases with increase of order.</p> <p>4) The intensity of dark fringes is not zero.</p>
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### Fraunhofer diffraction at single slit

Consider a slit AB of width 'e'. Let a plane wavefront WW<sup>1</sup> of monochromatic light of wavelength  $\lambda$  propagating normally towards the slit is incident on it. The diffracted light through the slit is focused by means of a convex lens on a screen placed in the focal plane of the lens. According to Huygens-Fresnel, every point on the wavefront in the plane of the slit is a source of secondary wavelets, which spread out to the right in all directions. These wavelets travelling normal to the slit, i.e., along the direction OP<sub>0</sub> are brought to focus at P<sub>0</sub> by the lens. Thus, P<sub>0</sub> is a bright central image. The secondary wavelets travelling at an angle  $\theta$  with the normal are focused at a point P<sub>1</sub> on the screen. Depending on path difference, the point P<sub>1</sub> may have maximum or minimum intensities. To find intensity at P<sub>1</sub>, let us draw the normal AC from A to the light ray at B.

The path difference between the wavelets from A & B in the direction  $\theta$  is given by

$$\text{Path difference} = BC = AB \sin \theta = e \sin \theta$$

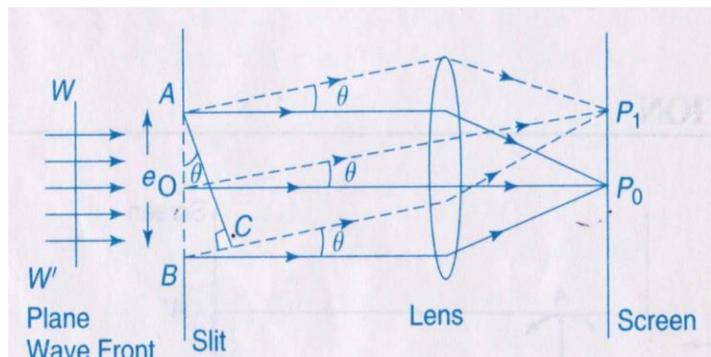
$$\begin{aligned} \text{Corresponding phase difference} &= \frac{2\pi}{\lambda} \times \text{path difference} \\ &= \frac{2\pi}{\lambda} e \sin \theta \end{aligned}$$

Let the width of the slit be divided into n equal parts and the amplitude of the wave from each part is 'a'. The phase difference between any two successive waves from these parts would be

$$\frac{1}{n} [\text{total phase}] = \frac{1}{n} \left[ \frac{2\pi}{\lambda} e \sin \theta \right] = \alpha$$

Using the method of vector addition of amplitudes, the resultant amplitude R is given by

$$\begin{aligned} R &= \frac{a \sin nd/2}{\sin d/2} \\ &= a \frac{\sin(\pi e \sin \theta / \lambda)}{\sin(\pi e \sin \theta / n\lambda)} \\ &= a \frac{\sin \alpha}{\sin \alpha/n} \text{ where } \alpha = \pi e \sin \theta / \lambda \\ &= a \frac{\sin \alpha}{\alpha/n} < \text{since } \alpha/n \text{ is very small}> \\ &= na \frac{\sin \alpha}{\alpha} \end{aligned}$$



$$= A \frac{\sin \alpha}{\alpha}$$

$$\text{Intensity} = I = R^2 = A^2 \left( \frac{\sin \alpha}{\alpha} \right)^2 \text{-----} \rightarrow (1)$$

### Principal maximum

The resultant amplitude R can be written in ascending powers of  $\alpha$  as

$$R = \frac{A}{\alpha} \left[ \alpha - \frac{\alpha^3}{3!} + \frac{\alpha^5}{5!} - \frac{\alpha^7}{7!} + \dots \dots \right]$$

$$= A \left[ 1 - \frac{\alpha^2}{3!} + \frac{\alpha^4}{5!} - \frac{\alpha^6}{7!} + \dots \dots \right]$$

I will be maximum, when the value of R is maximum. For maximum value of R, the negative terms must vanish i.e.,  $\alpha = 0$

$$\pi e \sin \theta / \lambda = 0$$

$$\sin \theta = 0$$

$$\theta = 0$$

$$\text{Then } R = A$$

$$\therefore I_{\max} = R^2 = A^2$$

The condition  $\theta = 0$  means that the maximum intensity is formed at  $P_0$  and is known as principal maximum.

### Minimum intensity position

I will be minimum, when  $\sin \alpha = 0$

$$\alpha = \pm\pi, \pm 2\pi, \pm 3\pi, \pm 4\pi, \dots \dots \dots$$

$$\alpha = \pm m\pi$$

$$\pi e \sin \theta / \lambda = \pm m\pi$$

$$e \sin \theta = \pm m\lambda \text{ where } m = 1, 2, 3, \dots \dots \dots$$

Thus, we obtain the points of minimum intensity on either side of the principal maximum. For  $m = 0$ ,  $\sin \theta = 0$ , which corresponds to principal maximum.

### Secondary maxima

In between these minima, we get secondary maxima. The positions can be obtained by differentiating the expression of I wrt  $\alpha$  and equating to zero. We get

$$\frac{dI}{d\alpha} = \frac{d}{d\alpha} \left[ A^2 \left( \frac{\sin \alpha}{\alpha} \right)^2 \right] = 0$$

$$A^2 2 \frac{\sin \alpha}{\alpha} \frac{\alpha \cos \alpha - \sin \alpha}{\alpha^2} = 0$$

$$\text{Either } \sin \alpha = 0 \text{ or } \alpha \cos \alpha - \sin \alpha = 0$$

$$\sin \alpha = 0 \text{ gives position of minima}$$

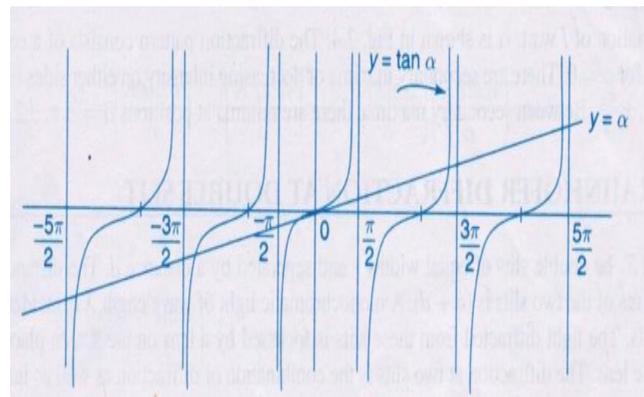
Hence the position of secondary maxima are given by

$$\alpha \cos \alpha - \sin \alpha = 0$$

$$\alpha =$$

$\tan \alpha$

The values of  $\alpha$  satisfying the above eqn are obtained graphically by plotting the curves  $y = \alpha$  and  $y = \tan \alpha$  on the same



graph. The points of intersection of the two curves gives the values of  $\alpha$  which satisfy the above equation. The plots of  $y = \alpha$  and  $y = \tan \alpha$  are shown in fig.

The points of intersection are

$$\alpha = 0, \pm \frac{3\pi}{2}, \pm \frac{5\pi}{2}, \pm \frac{7\pi}{2}, \dots$$

Using the above values in eqn (1), we get the intensities in various maxima.

$$\alpha = 0, I_0 = A^2 \quad (\text{principal maximum})$$

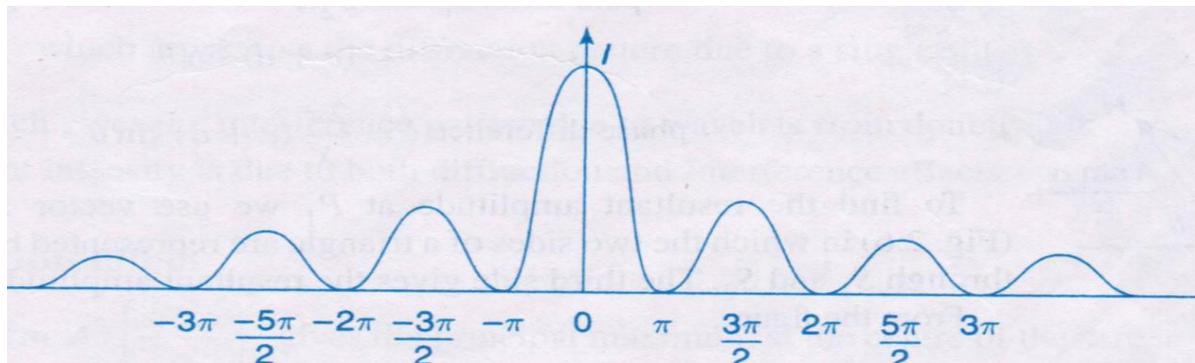
$$\alpha = \frac{3\pi}{2}, I_1 = A^2 \left[ \frac{\sin \frac{3\pi}{2}}{\frac{3\pi}{2}} \right]^2 \cong \frac{A^2}{22} \quad (\text{1st secondary maximum})$$

$$\alpha = \frac{5\pi}{2}, I_2 = A^2 \left[ \frac{\sin \frac{5\pi}{2}}{\frac{5\pi}{2}} \right]^2 \cong \frac{A^2}{62} \quad (\text{2nd secondary maximum})$$

and so on

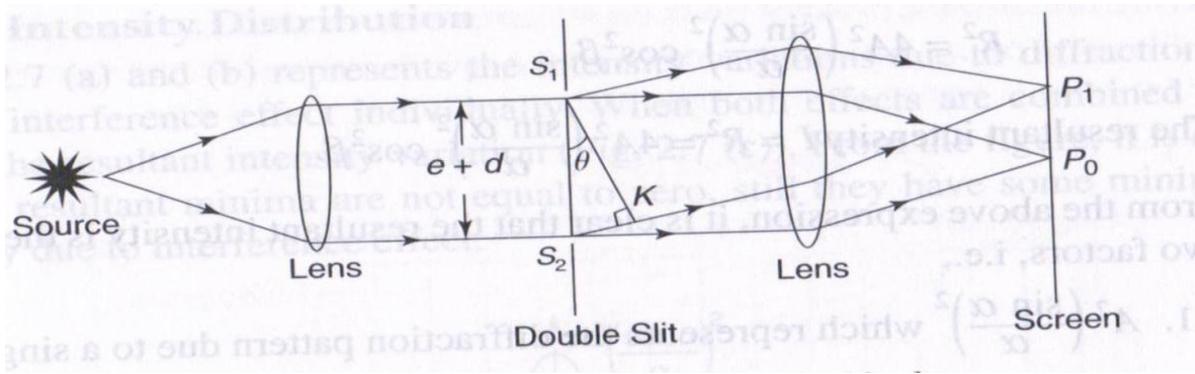
### Intensity distribution

The variation of  $I$  wrt  $\alpha$  is shown in fig. the diffraction pattern consists of a central principal maximum for  $\alpha = 0$ . There are secondary maxima of decreasing intensity on either of it at positions  $\alpha = \pm \frac{3\pi}{2}, \pm \frac{5\pi}{2}, \pm \frac{7\pi}{2}, \dots$ . Between secondary maxima, there are minima at positions  $\alpha = \pm \pi, \pm 2\pi, \dots$



### Fraunhofer diffraction at a double slits

Let  $S_1$  &  $S_2$  be double slits of equal widths 'e' and separated by a distance d. the distance between the middle points of the two slits is (e+d). A monochromatic light of wavelength  $\lambda$  is incident normally on the two slits. The light diffracted from these slits is focused by a lens on the screen placed in the focal plane of the lens. The diffraction at two slits is the combination of diffraction as well as interference, the pattern on the screen is the diffraction pattern due to a single slit on which a system of interference fringes is superimposed. When a plane wavefront is incident normally on two slits, the secondary wavelets from the slits travel uniformly in all directions. The wavelets travelling in the direction of incident light come to a focus at  $P_0$  while the wavelets travelling in a direction making an angle  $\theta$ , come to focus at  $P_1$ .



From the study of diffraction due to single slit, the resultant amplitude =  $A \frac{\sin \alpha}{\alpha}$  where  $\alpha = \frac{\pi e \sin \theta}{\lambda}$ . Since we use double slit, from each slit we get a wavelet of amplitude  $A \frac{\sin \alpha}{\alpha}$  in a direction  $\theta$ . These two wavelets interfere and meet at a point  $P_1$  on the screen. To calculate the path difference between the wavelets, let us draw a normal  $S_1K$  to the wavelets through  $S_2$ .

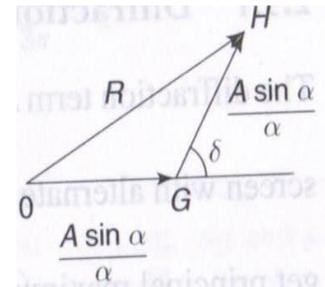
$$\begin{aligned} \text{Path diff} &= S_2K \\ &= (e+d)\sin \theta \end{aligned}$$

$$\text{Phase diff} = \frac{2\pi}{\lambda} (e+d)\sin \theta = \delta$$

To find the resultant amplitude at  $P_1$  we use vector addition method in which the two sides of a triangle are represented by the amplitudes through  $S_1$  &  $S_2$ . The third side gives the resultant amplitude. From the fig,

$$\begin{aligned} (OH)^2 &= (OG)^2 + (GH)^2 + 2(OG)(GH)\cos \delta \\ R^2 &= \left(A \frac{\sin \alpha}{\alpha}\right)^2 + \left(A \frac{\sin \alpha}{\alpha}\right)^2 + 2\left(A \frac{\sin \alpha}{\alpha}\right)\left(A \frac{\sin \alpha}{\alpha}\right) \cos \delta \\ &= 2A^2 \left(\frac{\sin \alpha}{\alpha}\right)^2 [1 + \cos \delta] \\ &= 2\left(A \frac{\sin \alpha}{\alpha}\right)^2 (1 + 2\cos^2 \delta / 2 - 1) \\ &= 4A^2 \left(\frac{\sin \alpha}{\alpha}\right)^2 \cos^2 \left(\frac{\pi(e+d)\sin \theta}{\lambda}\right) \end{aligned}$$

$$\begin{aligned} \text{Let } \beta &= \frac{\pi(e+d)\sin \theta}{\lambda} \\ R^2 &= 4A^2 \left(\frac{\sin \alpha}{\alpha}\right)^2 \cos^2 \beta \end{aligned}$$



$$\text{The resultant intensity } I = R^2 = 4A^2 \left(\frac{\sin \alpha}{\alpha}\right)^2 \cos^2 \beta$$

From the above expression, it is clear that the resultant intensity is the product of two factors, i.e.,

- 1)  $A^2 \left(\frac{\sin \alpha}{\alpha}\right)^2$  which represents the diffraction pattern due to a single slit.
- 2)  $\cos^2 \beta$  which gives the interference pattern due to wavelets from double slits. The resultant intensity is due to both diffraction and interference effects.

Diffraction effect

The diffraction term  $A^2\left(\frac{\sin \alpha}{\alpha}\right)^2$  gives the principal maximum at the centre of the screen with alternate minima and secondary maxima of decreasing intensity. We get principal maxima for  $\theta = 0$ . We get minima for  $\sin \alpha = 0$

$$\alpha = \pm m\pi$$

$$\pi e \sin \theta / \lambda = \pm m\pi$$

$$e \sin \theta = \pm m\lambda \text{ where } m = 1, 2, 3, \dots$$

The position of secondary maxima occurs for

$$\alpha = \pm \frac{3\pi}{2}, \pm \frac{5\pi}{2}, \pm \frac{7\pi}{2}, \dots$$

### Interference effect

The interference term  $\cos^2 \beta$  gives the equidistant bright and dark fringes. The maxima will occur for  $\cos^2 \beta = 1$

$$\beta = \pm n\pi$$

$$\pi(e + d) \sin \theta / \lambda = \pm n\pi$$

$$(e + d) \sin \theta = \pm n\lambda \text{ where } n = 0, 1, 2, 3, \dots$$

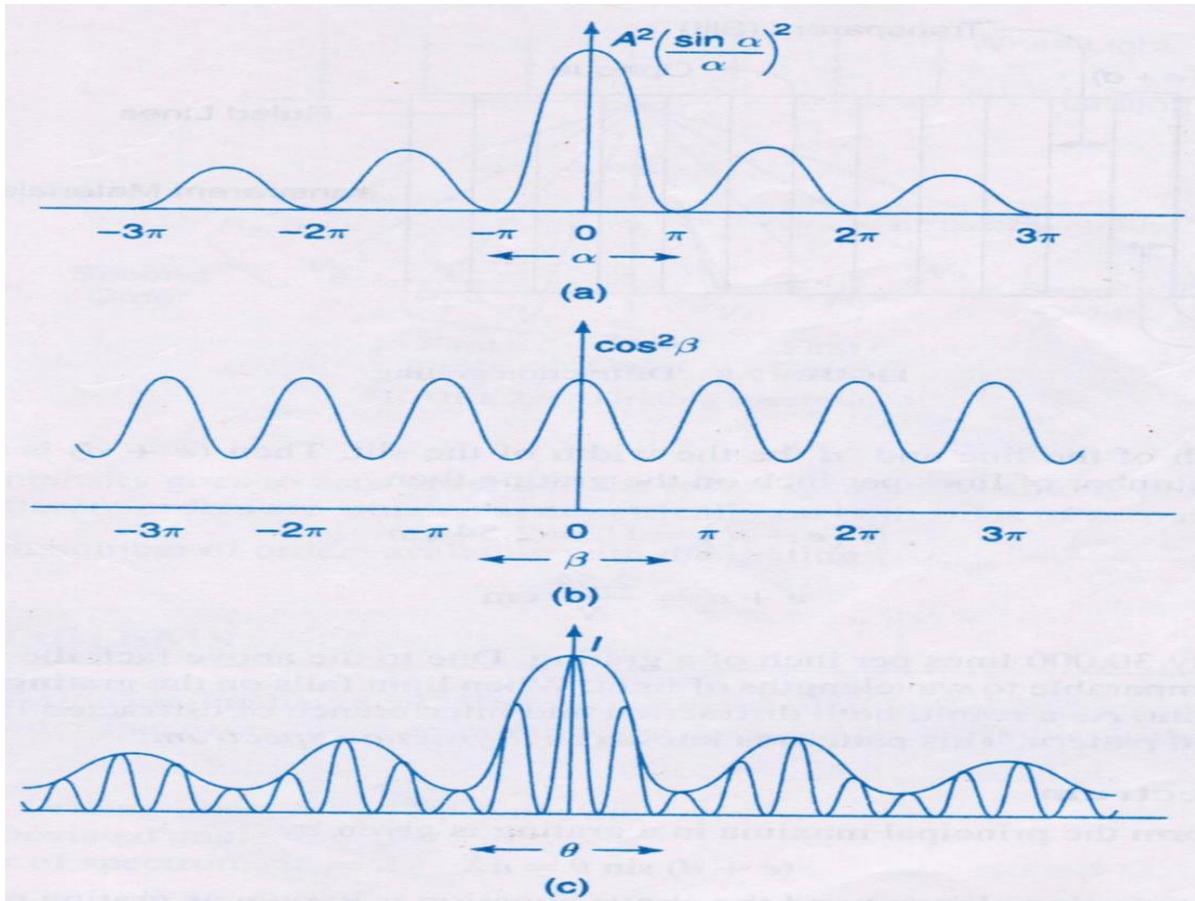
The minima will occur for  $\cos^2 \beta = 0$

$$\beta = \pm(2n+1)\pi/2 \text{ where } n = 0, 1, 2, \dots$$

$$(e + d) \sin \theta = \pm(2n+1)\lambda/2$$

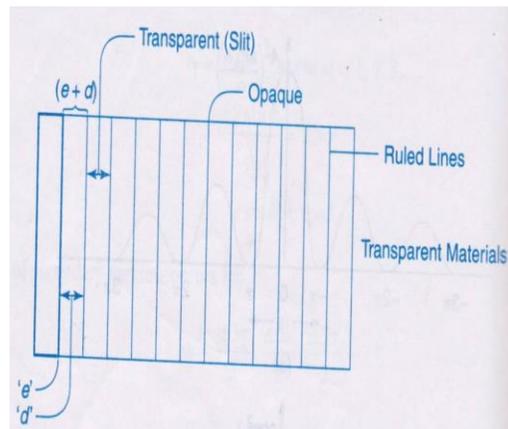
### Intensity distribution

When both effects are combined then we get the resultant intensity variation. From fig, it is clear that the resultant minima are not equal to zero, still they have some minimum intensity due to interference effect.



### Diffraction grating

An arrangement which consists of a large number of parallel slits of the same width and separated by equal opaque spaces is known as diffraction grating. Fraunhofer used the first grating consisting of a large number of parallel wires placed side by side very closely at regular intervals. Now gratings are constructed by ruling equidistant parallel lines on a transparent material such as glass with a fine diamond point. The ruled lines are opaque to light while the space between any two lines is transparent to light and act as a slit.



Let 'e' be the width of the line and 'd' be the width of the slit. Then (e+d) is known as grating element. If 'N' is the number of lines per inch on the grating then

$$N(e+d) = 1" = 2.54 \text{ cm}$$

$$(e+d) = \frac{2.54}{N} \text{ cm}$$

There will be nearly 30,000 lines per inch of a grating. Due to the above fact, the width of the slit is very narrow and is comparable to wavelengths of light. When light falls on the grating,

the light gets diffracted through each slit. As a result, both diffraction and interference of diffracted light gets enhanced and forms a diffraction pattern. This pattern is known as diffraction spectrum.

# UNIT-II

## **UNIT-II-Dielectric and Magnetic Properties of Materials**

### ***Introduction***

Dielectrics are insulating or non-conducting ceramic materials and are used in many applications such as capacitors, memories, sensors and actuators. Dielectrics are insulating materials that exhibit the property of electrical polarization, thereby they modify the dielectric function of the vacuum. A dielectric material is any material that supports charge without conducting it to a significant degree. In principle all insulators are dielectric, although the capacity to support charge varies greatly between different insulators. Although these materials do not conduct electrical current when an electric field is applied, they are not inert to the electric field. The field may cause a slight shift in the balance of charge within the material to form an electric dipole.

Thus the materials is called dielectric material.

Dielectric materials are used in many applications, from simple electrical insulation to sensors and circuit components.

Faraday was carried out the first numerical measurements on the properties of insulating materials when placed between the two parallel plates (capacitor), those materials, he called as dielectrics. He has found that the capacity of a condenser was dependent on the nature of the material separating the conducting surface. This discovery encouraged further empirical studies of insulating materials aiming at maximizing the amount of charge that can be stored by a capacitor. In search of suitable dielectric materials for specific applications, these materials have become increasingly concerned with the detailed physical mechanism governing the behavior of these materials.

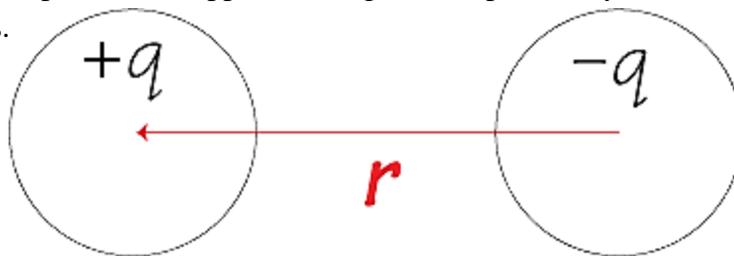
The difference between dielectric material and insulator depends on its application. Insulating materials are used to resist flow of current through it, on the other hand dielectric materials are used to store electrical energy. In contrast to the insulation aspect, the dielectric phenomena have become more general and fundamental, as it has the origin with the dielectric polarization.

### **Electric dipoles:**

Upon application of a dc or static electric field, there is a long range migration of charges. However, there is a limited movement of charges leading to the formation of charge dipoles and the material, in this state, is considered as polarized. These dipoles are aligned in the direction of the applied field. The net effect is called Polarization of the material.

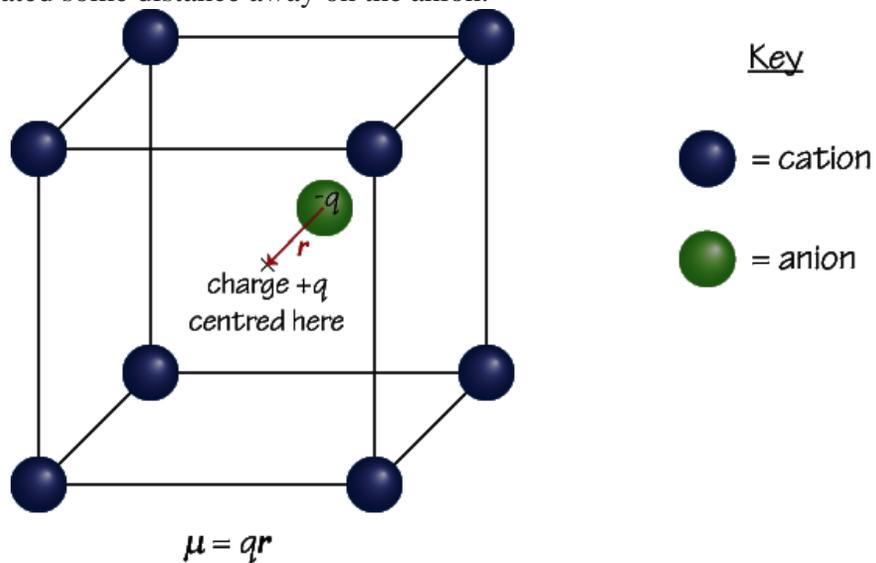
A dielectric supports charge by acquiring a polarisation in an electric field, whereby one surface develops a net positive charge while the opposite surface develops a net negative charge. This is made possible by the presence of electric dipoles – two opposite charges separated by a certain distance – on a microscopic scale.

1. If two discrete charged particles of opposite charges are separated by a certain distance, a dipole moment  $\mu$  arises.



$$\mu = qr$$

2. If the centre of positive charge within a given region and the centre of negative charge within the same region are not in the same position, a dipole moment  $\mu$  arises. For example, in the diagram below the centre of positive charge from the 8 cations shown is at X, while the centre of negative charge is located some distance away on the anion.



The second view of dipole moment is more useful, since it can be applied over a large area containing many charges in order to find the net dipole moment of the material.

The dipoles can be aligned as well as be induced by the applied field.

Note that in the equation for dipole moment,  $\mathbf{r}$  is a vector (the sign convention is that  $\mathbf{r}$  points from negative to positive charge) therefore the dipole moment  $\boldsymbol{\mu}$  is also a vector

***Electric field intensity or electric field strength ( E )***

The force experienced by a unit test charge is known as electric field strength E

$$E = \frac{Q}{4\pi\epsilon r^2} \dots\dots(1)$$

where  $\epsilon$  is the permittivity or dielectric constant of the medium in which electric charge is placed. For vacuum  $\epsilon = \epsilon_0 = 8.854 \times 10^{-12} \text{Fm}^{-1}$

***Electric flux density or electric displacement vector ( D )***

The electric flux density or electric displacement vector is the number of flux lines crossing normal to a unit surface area. The electric flux density at a distance from the point charge Q is

$$D = \frac{Q}{4\pi r^2} \dots\dots(2)$$

then from (1) and (2)  $D = \epsilon E \dots\dots (3)$

***Dielectric constant (εr)***

The dielectric constant of a material is defined as the ratio of the permittivity of the medium ( $\epsilon$ ) to the permittivity of free space ( $\epsilon_0$ ). It can also defined as the ratio of the capacitance with dielectric ( $C_d$ ) and with air ( $C_A$ ) between the plates.

$$\epsilon_r = \frac{\epsilon}{\epsilon_0} = \frac{C_d}{C_A} \dots\dots(4)$$

**Capacitance:** The property of a conductor or system of conductor that describes its ability to store electric charge.

$$C = q / V = A \epsilon / d \quad \text{where}$$

- C is capacitance of capacitor
- q is charge on the capacitor plate
- V is potential difference between plates
- A is area of capacitor plate
- $\epsilon$  is permittivity of medium
- d is distance between capacitor plates

Units: Farad .

***Polarization***

When an electric field is applied to a material with dielectrics, the positive charges are displaced opposite to the direction of the field and negative charges displaced in the direction of the field. The displacement of these two charges create a local dipole, creation of dipole by applying electric field is called as polarization.

Polarization is defined as induced dipole moment per unit volume.

$$P = \frac{\sum \mu}{\text{Volume}} \quad \dots(5)$$

**Polarisability**

The polarization  $P$  is directly proportional to the electric field strength  $E$

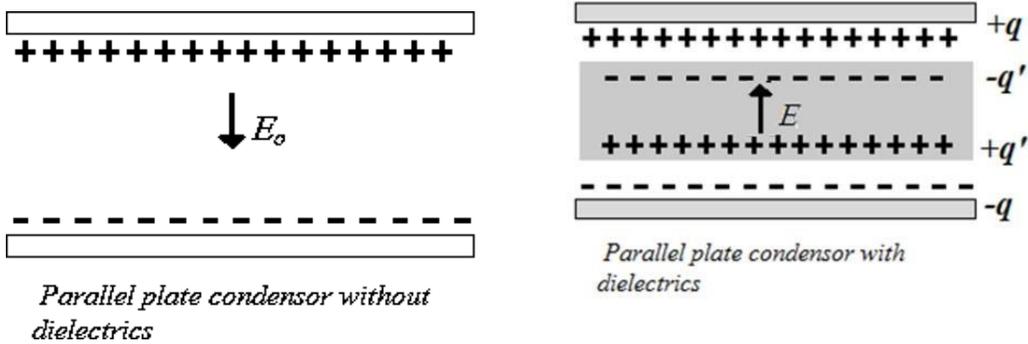
$$P \propto E$$

$$P = \alpha E \quad \dots(6)$$

Where  $\alpha$  proportionality is constant called as polarisability. The polarisability is defined as polarization per unit applied electric field. If the material contains  $N$  number of dipoles per unit volume then

$$P = N\alpha E \quad \dots(7)$$

**Relation between polarization and dielectric constant**



Let us apply Gauss theorem for parallel plate condenser.

$$\int E_0 dA = \frac{q}{\epsilon_0}$$

$$E_0 A = \frac{q}{\epsilon_0}$$

$$E_0 = \frac{q}{A\epsilon_0} = \frac{\sigma}{\epsilon_0} \quad \dots(1)$$

Where  $\sigma$  is the charge per unit area.

Let a dielectric slab placed between two plates. Due to polarization, charges appear on the two faces of the slab, and establish yet another field within the dielectric media. Let this field be  $E'$ . The direction of  $E'$  will be opposite to that of  $E_0$ .

The resultant field  $E$  in the material can be written as,

$$E = E_0 - E' \quad \dots(2)$$

If  $\sigma_p$  is the charge/unit area on the inserted dielectric slab surfaces, then by following equation (1), we write,

$$E' = \frac{q}{A\epsilon_0} = \frac{\sigma_p}{\epsilon_0} \dots\dots\dots(3)$$

From (1), (2) and (3),

$$E = \frac{\sigma}{\epsilon_0} - \frac{\sigma_p}{\epsilon_0}$$

or

$$\epsilon_0 E = \sigma - \sigma_p \dots\dots\dots(4)$$

Since the magnitude of polarization  $P =$  dipole moment/ Unit Volume

But dipole moment = induced charge X distance

Therefore

$$P = \text{induced charge/ Area} = \sigma_p$$

We know that electric displacement field or electric flux density  $D$  is given by charge /unit area

$$D = q/A = \sigma$$

Therefore Equation 4 becomes

$$\epsilon_0 E = D - P$$

$$P = D - E\epsilon_0 \dots\dots(5)$$

in free space where there is no dielectric  $P=0$

$$D = E\epsilon_0$$

But in dielectric media the  $D$  changes. From electrostatics

$$D = \epsilon_0 \epsilon_r E$$

From (3)

$$P = E\epsilon_0 \epsilon_r - E\epsilon_0$$

$$P = E\epsilon_0 (\epsilon_r - 1) \dots\dots\dots(6)$$

$$(\epsilon_r - 1) = \frac{P}{E\epsilon_0} \equiv \chi$$

Where  $\chi$  is electric susceptibility of the dielectric medium. It doesn't have any units.

Since  $P$  and  $E$  are vectors eqn (6) can be written as

$$\bar{P} = \bar{E}\varepsilon_0(\varepsilon_r - 1) \dots(7)$$

This equation represents polarization vector.

### ***Types of polarization***

Dielectric polarization is the displacement of charge particles with the applied electric field. The displacement of electric charges results in formation of electric dipole moment in atoms, ions or molecules of the material. There are four different types of polarization, they are listed below.

1. Electric polarization,
2. Ionic polarization,
3. Orientation polarization
4. Space charge polarization

### ***Electric polarization***

The displacement of the positively charged nucleus and the negatively charged electrons of an atom in opposite directions, on application of an electric field, result in electronic polarization.

On applying a field, the electron cloud around the nucleus shifts towards the positive end of the field. As the nucleus and electron cloud are separated by a distance, dipole moment is created within each atom. The extent of this shift is proportional to the field strength.

Induced dipole moment

$$\mu_e \propto E$$

$$\mu_e = \alpha_e E$$

Where  $\alpha_e$  is called electronic polarizability.

The dipole moment per unit volume is called electronic polarization.

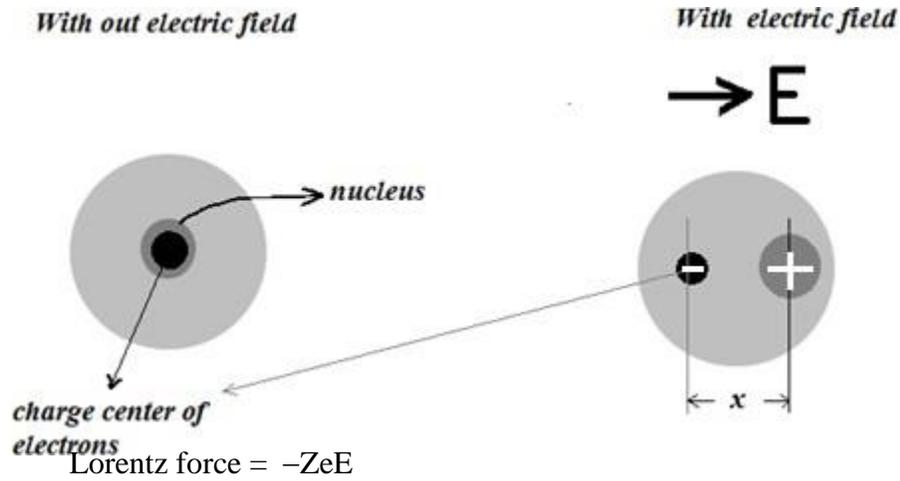
- It increases with increase of volume of the atom.
- This kind of polarization is mostly exhibited in monoatomic gases.(e.g. He, Ne, Ar, Kr, Xe etc..)
- It is independent of temperature.
- It occurs only at optical frequencies ( $10^{15}$ Hz)
- Vast fast process:  $10^{-15} \sim 10^{-16}$ s.

### ***Calculation of electronic polarizability:***

Electronic polarization can be explained by classical model of an atom in gasses. In gasses the atoms are assumed that the interaction among the atoms is negligible. Here the nucleus of charge  $Ze$  is surrounded by an electron cloud of charge  $-Ze$  distributed in the sphere of radius  $R$ .

$$\text{Charge density, } \rho = -\frac{Ze}{(4/3)\pi R^3} \quad \dots(1)$$

When an electric field  $E$  is applied, the nucleus and electrons experience Lorentz force of magnitude  $ZeE$  in opposite direction. Therefore the nucleus and electrons are pulled apart. As they are pulled apart a Coulomb force develops between them. At equilibrium these two forces are equal and nucleus and electron cloud are separated by a small distance  $x$ .



$$\text{Coulomb Force} = Ze \times \frac{\text{Charge enclosed in hemisphere of radius } x}{4\pi\epsilon_0 x^2}$$

$$\text{The charge enclosed} = \frac{4}{3}\pi x^3 \rho$$

$$\begin{aligned} \text{From equation (1)} &= \frac{4}{3}\pi x^3 \left[ -\frac{3}{4} \left( \frac{Ze}{\pi R^3} \right) \right] \\ &= -\frac{Zex^3}{R^3} \end{aligned}$$

Hence Coulomb force is =  $\frac{Ze}{4\pi\epsilon_0 x^2} \times -\frac{Zex^3}{R^3} = -\frac{Ze^2 x^2}{4\pi\epsilon_0 R^3} \dots(3)$

At equilibrium Lorentz force = Coulomb force (equation (2) equal to (3))

$$-ZeE = -\frac{Z^2 e^2 x}{4\pi\epsilon_0 R^3}$$

$$x = \frac{4\pi\epsilon_0 R^3 E}{Ze} \dots(4)$$

The displacement of the electron cloud is proportional to applied electric field.

The electric dipole moment  $\mu_e = Zex = \frac{Ze4\pi\epsilon_0 R^3 E}{Ze}$

$$\mu_e = 4\pi\epsilon_0 R^3 E$$

$$\mu_e \propto E$$

$$\mu_e = \alpha_e E \dots(5)$$

Where  $\alpha_e = 4\pi\epsilon_0 R^3$  is called electronic polarizability.

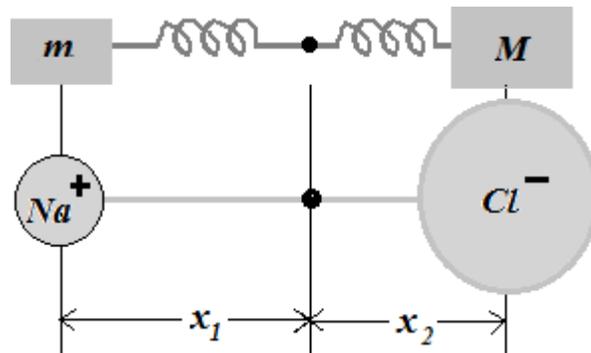
$$P_e = N\mu_e = N\alpha_e E$$

Where N is the number of atoms/m<sup>3</sup>

But polarization  $P = E\epsilon_0(\epsilon_r - 1) = N\alpha_e E$

$$(\epsilon_r - 1) = \frac{N\alpha_e}{\epsilon_0} \text{ or } \alpha_e = \frac{(\epsilon_r - 1)\epsilon_0}{N}$$

## Ionic Polarization



Ionic polarization occurs in ionic solids such as NaCl, KBr, and LiBr. When an electric field is applied to an ionic solid the positive and negative ions displace to their respective polarities creating an electric dipole this is called as ionic polarization.

In the absence of an electric field there is no displacement of ions. When an electric field is applied an induced dipole moment  $\mu_i$  is produced.

Let  $x_1$  and  $x_2$  be the displacement of positive and negative ion respectively. Then the induced dipole moment.

$$\mu_i = e(x_1 + x_2) \quad \dots(6)$$

Let F be restoring force F

$$\begin{aligned} &\propto x_1 \\ &\propto x_2 \\ &= \beta_1 x_1 \\ &= \beta_2 x_2 \end{aligned}$$

From mechanics the spring constant of mass attached to a spring is given by  $\beta = m\omega^2$

At equilibrium the Lorentz force = restoring force

$$eE = m\omega_0^2 x$$

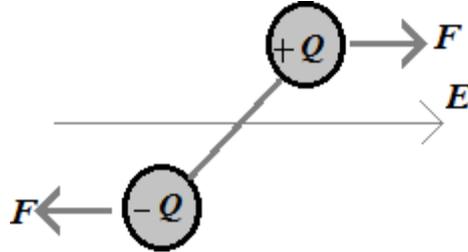
Therefore  $x = \frac{eE}{m\omega_0^2}$       Then  $x_1 = \frac{eE}{m\omega_0^2}$        $x_2 = \frac{eE}{M\omega_0^2}$

$$\mu = \frac{e^2}{\omega_0^2} \left[ \frac{1}{m} + \frac{1}{M} \right] E = \alpha_i E \quad \dots(7)$$

Where  $\alpha_i = \frac{e^2}{\omega_0^2} \left[ \frac{1}{m} + \frac{1}{M} \right]$  is called as ionic polarisability ... (8)

## Orientation Polarization

Orientation polarization occurs only in polar molecules (the molecules which have permanent dipole moment eg H<sub>2</sub>O, Phenol, etc.). When an electric field is applied to a polar molecule, the dipoles experience a torque and try to align parallel to the applied field.



Consider a polar molecule subjected to an electric field  $E$ . The alignment of electric dipole with the electric field is similar to the alignment of magnetic dipole with the applied magnetic field in paramagnetic material.

The expression for polarization can be obtained from the theory of paramagnetism.

The orientation polarization is given as

$$P = \frac{N\mu^2 E}{3KT} = \alpha E \quad \dots(9)$$

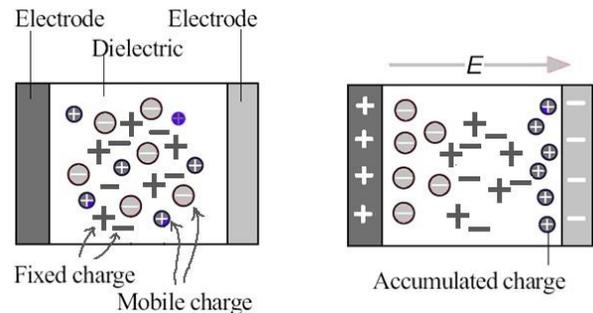
$$\text{Where } \alpha = \frac{\mu^2}{3KT} \text{ is called as orientation polarisability} \quad \dots(10)$$

## Space charge polarization

Space charge polarization occurs due to the accumulation of charges at the electrodes or at interfaces in a multiphase materials.

In the presence of an applied field, the mobile positive ions and negative ions migrate toward the negative electrode and positive electrode respectively to an appreciable distance giving rise to redistribution of charges, but they remain in the dielectric material (electrode is blocking).

The space charge polarization can be defined as the redistribution of charges due to the applied electric field and the charges accumulate on the surface of the electrodes. It occurs when the rate of charge accumulation is different from rate of charge removal. Space charge polarization is not significant in most of the dielectric materials.



## Internal field in liquids and solids (one dimensional)

In gases state the atoms are separated by large distances and the interaction between the atoms can be neglected. When an external electric field  $E$  is applied, the intensity of the electric field experienced by an atom in gases state will be equal to the applied electric field  $E$ .

In solids and liquids, the atoms are close to each other leading to strong interaction between them. In solids and liquids the intensity of the electric field at a given point of the material is not equal to the applied electric field but equal to internal field which is the sum of applied electric field and field due to other dipoles present in the material.

$$\text{Internal field } E_i = E + E' \quad \dots(1)$$

The internal field can be calculated by Epstein model in the case of one dimensional atomic array.

## Electric field along the axis of an electric dipole

Consider an electric dipole of length  $2d$  and charge  $Q$ , the field along the axis of the dipole at point A is the sum of the electric field due to  $+Q$  and  $-Q$ .

$$\text{The electric field due to } +Q \text{ at point A is } E^+ = \frac{Q}{4\pi\epsilon_0(x-d)^2}$$

$$\text{The electric field due to } -Q \text{ at point A is } E^- = \frac{Q}{4\pi\epsilon_0(x+d)^2}$$

$$\text{Electric field of dipole at A is } E = E^+ - E^- = \frac{Q}{4\pi\epsilon_0} \left[ \frac{1}{(x-d)^2} - \frac{1}{(x+d)^2} \right]$$

$$\frac{2Q}{4\pi\epsilon_0} \left[ \frac{2dx}{(x-d)^2(x+d)^2} \right]$$

since  $x \gg d$   $(x-d)^2 \approx (x+d)^2 \approx x^2$  then

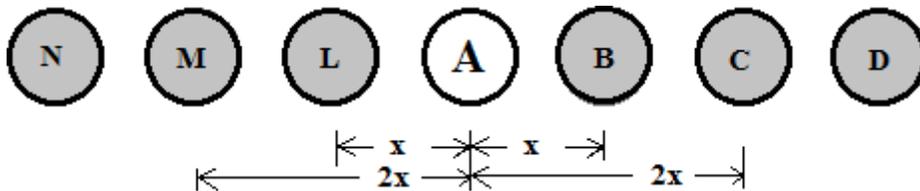
$$\frac{2Q}{4\pi\epsilon_0} \left[ \frac{2dx}{x^4} \right] = \frac{4dQ}{4\pi\epsilon_0 x^3}$$

since  $2dQ = \mu_i$

$$\frac{2\mu_i}{4\pi\epsilon_0 x^3}$$

.....(2)

Consider an array of one dimensional atoms along x- axis. The all the atoms are similar, equally spaced and have induced electric dipole moment  $\mu_i$  in an applied electric field  $E$ . The electric field experienced at the A is the sum of electric fields of other dipoles and applied electric field  $E$ .



The electric field at A due to the induced dipole B and L which are at a distance x is

$$E_B = E_L = \frac{2\mu_i}{4\pi\epsilon_0 x^3}$$

The electric field at A due to the induced dipole C and M which are at a distance 2x is

$$E_C = E_M = \frac{2\mu_i}{4\pi\epsilon_0 (2x)^3}$$

Therefore the field due to other dipoles is

$$E' = E_B + E_L + E_C + E_M + E_D + E_N + \dots \quad \text{.....(3)}$$

$$E' = \frac{2\mu_i}{4\pi\epsilon_0 x^3} + \frac{2\mu_i}{4\pi\epsilon_0 x^3} + \frac{2\mu_i}{4\pi\epsilon_0^3 (2x)^3} + \frac{2\mu_i}{4\pi\epsilon_0^3 (2x)^3} + \frac{2\mu_i}{4\pi\epsilon_0^3 (3x)^3} + \frac{2\mu_i}{4\pi\epsilon_0^3 (3x)^3} + \dots$$

$$E' = \frac{4\mu_i}{4\pi\epsilon_0 x^3} + \frac{4\mu_i}{4\pi\epsilon_0^3 (2x)^3} + \frac{4\mu_i}{4\pi\epsilon_0^3 (3x)^3} + \dots$$

$$E' = \frac{\mu_i}{\pi\epsilon_0 x^3} \left[ 1 + \frac{1}{2^3} + \frac{1}{3^3} + \frac{1}{4^3} + \frac{1}{5^3} + \dots \right] \quad \text{where } 1 + \frac{1}{2^3} + \frac{1}{3^3} + \frac{1}{4^3} + \frac{1}{5^3} + \dots = 1.2$$

$$E' = \frac{1.2\mu_i}{\pi\epsilon_0 x^3}$$

$$\text{Therefore the internal field } E = E + \frac{1.2\mu_i}{\pi\epsilon_0 x^3} \quad \text{.....(4)}$$

The local field in a three dimensional solid is similar the above equation the number density  $N$  of atoms replaces  $1/a^3$ . Since  $N\mu_i = P$  and  $1.2/\pi$  is replaced by  $\gamma$ . Then the internal field is

$$E_i = E + \frac{1.2N\mu_i}{\pi\epsilon_0} = E + \frac{1.2P}{\pi\epsilon_0} = E + \frac{\gamma P}{\epsilon_0}$$

$\gamma$  depends on the internal structure For a cubic symmetry crystal  $\gamma$  value is  $1/3$

$$E_i = E + \frac{P}{3\epsilon_0} \quad \dots(5)$$

The field given by the above equation is called Lorentz field.

### ***Clausius - Mosotti equation***

Let us consider elemental solid dielectric which exhibits only electronic polarization. If  $\alpha_e$  is the electronic polarisability per atom, it is related to the bulk polarization  $P$  through the relation

$$P = N\alpha_e E_i \quad \dots(6)$$

$$\alpha_e = \frac{P}{NE_i} \quad \dots(7)$$

Where  $N$  is the number of atoms per unit volume and  $E_i$  is the local field using the relation (5)

$$\alpha_e = \frac{P}{N \left[ E + \frac{P}{3\epsilon_0} \right]} \quad \dots(8)$$

By using the relation between the polarization and permittivity we have

$$P = E\epsilon_0(\epsilon_r - 1) \quad \dots(9)$$

$$E = \frac{P}{\epsilon_0(\epsilon_r - 1)} \quad \dots(10)$$

Substitute the value of  $E$  from (10) in (8)

$$\alpha_e = \frac{N \left[ \frac{P}{\epsilon(\epsilon-1)} + \frac{P}{\epsilon} \right]}{3\epsilon_0}$$

$$\frac{N\alpha_e}{\epsilon_0} = \frac{1}{\left[ \frac{1}{(\epsilon^e-1)} + \frac{1}{3} \right]} = \frac{1}{\left[ \frac{\epsilon_r + 2}{3(\epsilon^e-1)} \right]}$$

$$\boxed{\begin{matrix} \epsilon_r - 1 \\ \epsilon_r + 2 \end{matrix} = \frac{N\alpha_e}{3\epsilon_0}} \quad \dots(11)$$

The above equation is known as Clausius Mosotti equation which is valid for nonpolar solids

**Dielectric loss:**

Dielectric loss is the dissipation of energy through the movement of charges in an alternating electromagnetic field as polarisation switches direction.

An efficient dielectric supports a varying charge with minimal dissipation of energy in the form of heat is called dielectric loss. There are two main forms of loss that may dissipate energy within a dielectric. In conduction loss, a flow of charge through the material causes energy dissipation.

Dielectric loss is especially high around the relaxation or resonance frequencies of the polarisation mechanisms as the polarisation lags behind the applied field, causing an interaction between the field and the dielectric's polarisation that results in heating. This is illustrated by the diagram below (recall that the dielectric constant drops as each polarisation mechanism becomes unable to keep up with the switching electric field.)

**Dielectric loss quantifies a dielectric material's inherent dissipation of electromagnetic energy into, e.g., heat.**

**It can be represented in terms loss tangent  $\tan \delta$  and is defined:**

$$\tan \delta_e = \frac{\epsilon''}{\epsilon'}$$

**Dielectric Breakdown :** The dielectric breakdown is the sudden change in state of a dielectric material subjected to a very high electric field , under the influence of which , the electrons are lifted into the conduction band causing a surge of current , and the ability of the material to resist the current flow suffers a breakdown .

Or

When a dielectric material loses its resistivity and permits very large current to flow through it, then the phenomenon is called dielectric breakdown

Or

At high electric fields, a material that is normally an electrical insulator may begin to conduct electricity – i.e. it ceases to act as a dielectric. This phenomenon is known as dielectric breakdown.

### **Frequency dependence of polarizability:**

On application of an electric field, polarization process occurs as a function of time. The polarization  $P(t)$  as a function of time. The polarization  $P(t)$  as a function of time  $t$  is given by

$$P(t) = P[1 - \exp(-t / t_r)]$$

Where  $P$  – max. Polarization attained on prolonged application of static field.  $t_r$  - relaxation time for particular polarization process

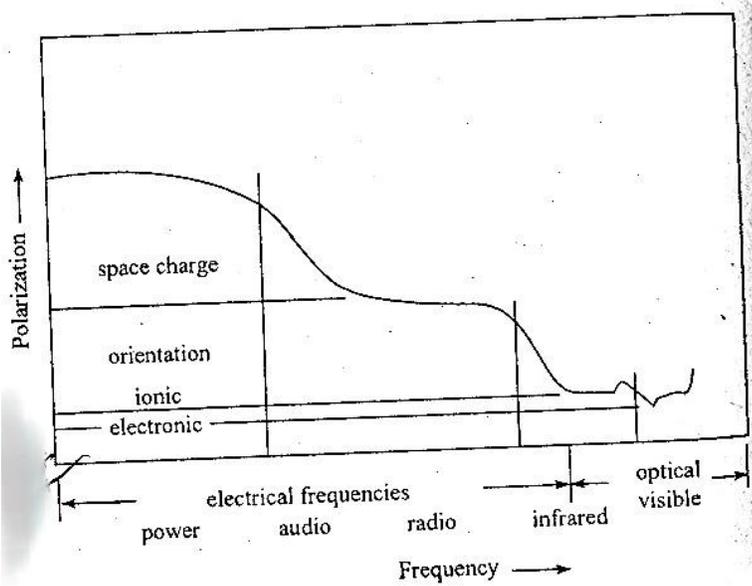
The relaxation time  $t_r$  is a measure of the time scale of polarization process. It is the time taken for a polarization process to reach 0.63 of the max. value.

Electronic polarization is extremely rapid. Even when the frequency of the applied voltage is very high in the optical range ( $\approx 10^{15}$  Hz), electronic polarization occurs during every cycle of the applied voltage.

Ionic polarization is due to displacement of ions over a small distance due to the applied field. Since ions are heavier than electron cloud, the time taken for displacement is larger. The frequency with which ions are displaced is of the same order as the lattice vibration frequency ( $\approx 10^{13}$  Hz). Hence, at optical frequencies, there is no ionic polarization. If the frequency of the applied voltage is less than  $10^{13}$  Hz, the ions respond.

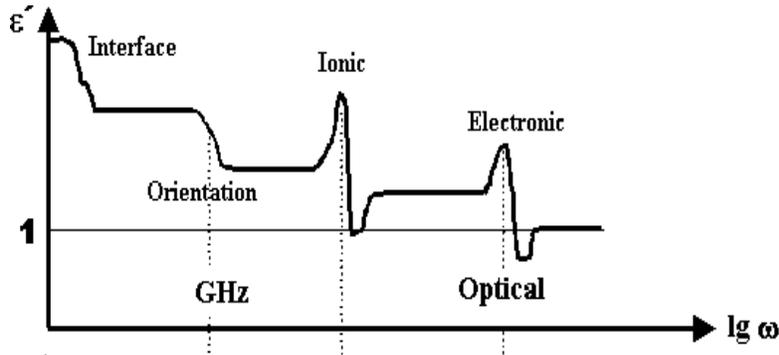
Orientation polarization is even slower than ionic polarization. The relaxation time for orientation polarization in a liquid is less than that in a solid. Orientation polarization occurs, when the frequency of applied voltage is in audio range (10<sup>10</sup> Hz).

Space charge polarization is the slowest process, as it involves the diffusion of ions over several interatomic distances. The relaxation time for this process is related to frequency of ions under the influence of applied field. Space charge polarization occurs at power frequencies (50-60 Hz).



## Frequency Dependence of dielectric constant

When a dielectric material is subjected to an alternating field, the polarization component required to follow the field in order to contribute to the total polarization of the dielectrics. The relative permittivity which is a measure of the polarization also depends on the frequency. The dependence of  $\epsilon_r$  on frequency of the electric field is shown in the figure.



At very low frequency, the dipoles will get sufficient time to orient themselves completely with the field and all types of polarization exist. Since the dielectric is characterized by polarisability  $\alpha$  ( $\alpha = \alpha_e + \alpha_i + \alpha_o$ ) at low frequency i.e at radiofrequency region the dielectric constant will be due to all polarisability.

The orientation polarization, which is effective at low frequencies, is damped out for higher frequencies. In the microwave region the dipoles fail to follow the field and the polarisability reduces to ( $\alpha = \alpha_e + \alpha_i$ ), as a result  $\epsilon_r$  decreases to some amount.

In the IR region the ionic polarization fails to follow the field so the contribution of ionic polarization dies away. In this region only electronic polarization contributes to the total polarization. Therefore ( $\alpha = \alpha_e$ ) the  $\epsilon_r$  still decreases and only electronic polarization exist.

We know that

$$P = N\alpha_e E = \epsilon_o (\epsilon_r - 1)E$$

Then the relative permittivity is

$$\epsilon_r = 1 + \frac{N\alpha_e}{\epsilon_o} \quad \dots(1)$$

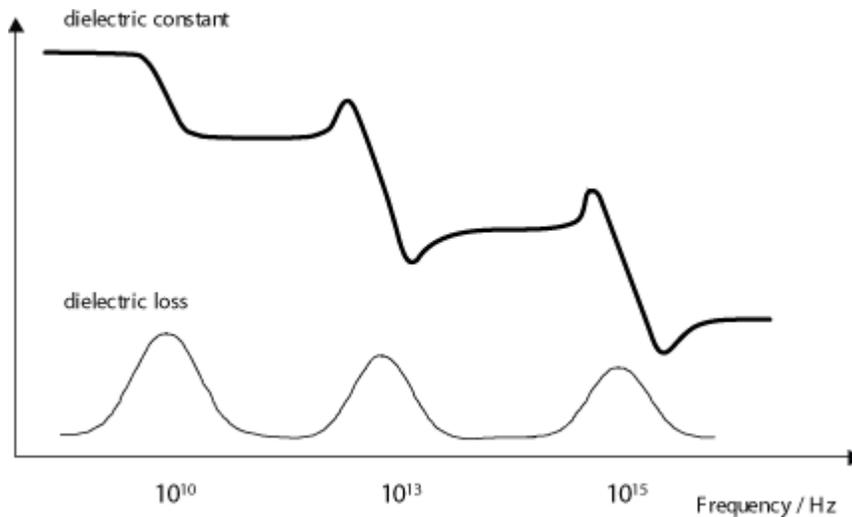
In the ultraviolet region even the electron cloud could not follow the field and electronic polarisability becomes almost zero and the permittivity becomes one.

$$[\epsilon_r]_{X\text{-ray}} = 1$$

For example at low frequency the dielectric constant of water at room temperature is about 80, but it fall to about 1.8 in the optical region.

### ***Frequency Dependence of dielectric loss:***

Dielectric loss tends to be higher in materials with higher dielectric constants. This is the downside of using these materials in practical applications. Dielectric loss is utilised to heat food in a microwave oven: the frequency of the microwaves used is close to the relaxation frequency of the orientational polarisation mechanism in water, meaning that any water present absorbs a lot of energy that is then dissipated as heat. The exact frequency used is slightly away from the frequency at which maximum dielectric loss occurs in water to ensure that the microwaves are not all absorbed by the first layer of water they encounter, therefore allowing more even heating of the food.



### ***Ferroelectrics***

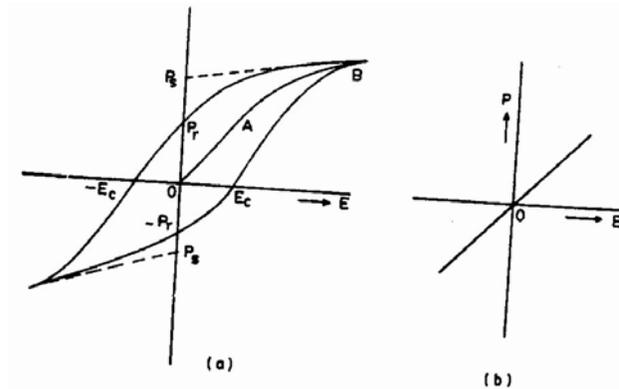
Below certain temperature it is found that some materials spontaneously acquire an electric dipole moment. These materials are called as ferroelectric materials or ferroelectrics. The temperature at which ferroelectric property of the material disappears is called as ferroelectric Curie temperature.

Ferroelectric materials are anisotropic crystals which exhibit a hysteresis curve P versus E which can be explained by domain hypothesis.

**Ferro electricity:** Ferro electric materials are an important group not only because of intrinsic Ferro electric property, but because many possess useful piezo electric, birefringent and electro optical properties.

The intrinsic Ferro electric property is the possibility of

reversal or change of orientation of the polarization direction by an electric field. This leads to hysteresis in the polarization  $P$ , electric field  $E$  relation, similar to magnetic hysteresis. Above a critical temperature, the Curie point  $T_c$ , the spontaneous polarization is destroyed by thermal disorder. The permittivity shows a characteristic peak at  $T_c$ .



**Piezo – Electric Materials and Their Applications:** Single crystal of quartz is used for filter, resonator and delay line applications. Natural quartz is now being replaced by synthetic material.

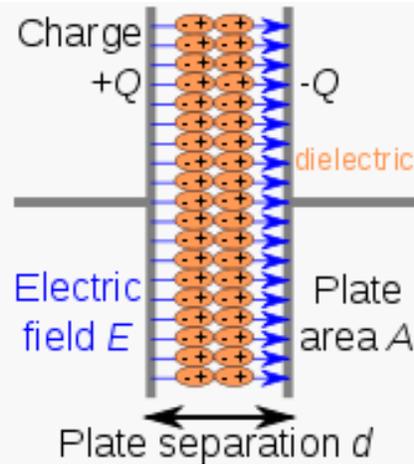
Rochelle salt is used as transducer in gramophone pickups, ear phones, hearing aids, microphones etc. the commercial ceramic materials are based on barium titanate, lead zirconate and lead titanate. They are used for high voltage generation (gas lighters), accelerometers, transducers etc. Piezo electric semiconductors such as GaS, ZnO & CdS are used as amplifiers of ultrasonic waves.

### Applications of Dielectric Materials:

Almost any type of electrical equipment employs dielectric materials in some form or another. Wires and cables that carry electrical current, for example, are always coated or wrapped with some type of insulating (dielectric) material. Sophisticated electronic equipment such as rectifiers, semiconductors, transducers, and amplifiers contain or are fabricated from dielectric materials. The insulating material sandwiched between two conducting plates in a capacitor is also made of some dielectric substance.

Liquid dielectrics are also employed as electrical insulators. For example, transformer oil is a natural or synthetic substance (mineral oil, silicone oil, or organic esters, for example) that has the ability to insulate the coils of a transformer both electrically and thermally.

## 1. Capacitors



Charge separation in a parallel-plate capacitor causes an internal electric field. A dielectric (orange) reduces the field and increases the capacitance.

Commercially manufactured capacitors typically use a solid dielectric material with high permittivity as the intervening medium between the stored positive and negative charges. This material is often referred to in technical contexts as the *capacitor dielectric*.

The most obvious advantage to using such a dielectric material is that it prevents the conducting plates, on which the charges are stored, from coming into direct electrical contact. More significantly, however, a high permittivity allows a greater stored charge at a given voltage. This can be seen by treating the case of a linear dielectric with permittivity  $\epsilon$  and thickness  $d$  between two conducting plates with uniform charge density  $\sigma_\epsilon$ . In this case the charge density is given by

$$\sigma_\epsilon = \epsilon \frac{V}{d}$$

and the capacitance per unit area by

$$c = \frac{\sigma_\epsilon}{V} = \frac{\epsilon}{d}$$

From this, it can easily be seen that a larger  $\epsilon$  leads to greater charge stored and thus greater capacitance.

Dielectric materials used for capacitors are also chosen such that they are resistant to ionization. This allows the capacitor to operate at higher voltages before the insulating dielectric ionizes and begins to allow undesirable current.

## 2. Dielectric resonator

A *dielectric resonator oscillator* (DRO) is an electronic component that exhibits resonance of the polarization response for a narrow range of frequencies, generally in the microwave band. It consists of a "puck" of ceramic that has a large dielectric constant and a low dissipation factor.

Such resonators are often used to provide a frequency reference in an oscillator circuit. An unshielded dielectric resonator can be used as a Dielectric\_Resonator Antenna (DRA).

### 3. Insulators-

**Required Qualities of Good Insulating Materials:** The required qualities can be classified as under electrical, mechanical, thermal and chemical applications.

- i) Electrical:
  1. electrically the insulating material should have high electrical resistivity and high dielectric strength to withstand high voltage.
  2. The dielectric losses must be minimum.
  3. Liquid and gaseous insulators are used as coolants. For example transformer oil, hydrogen and helium are
- ii) Mechanical:
  1. insulating materials should have certain mechanical properties depending on the use to which they are put.
  2. When used for electric machine insulation, the insulator should have sufficient mechanical strength to withstand vibration.
- iii) Thermal: Good heat conducting property is also desirable in such cases. The insulators should have small thermal expansion and it should be non-ignitable.
- iv) Chemical:
  1. chemically, the insulators should be resistant to oils, liquids, gas fumes, acids and alkali's.
  2. The insulators should be water proof since water lowers the insulation resistance and the dielectric strength.

#### **Other Applications:**

Solid dielectrics are perhaps the most commonly used dielectrics in electrical engineering, as very good insulators. Some examples include porcelain, glass, and most plastics.

Air, nitrogen and sulfur hexafluoride are the three most commonly used gaseous dielectrics.

Industrial coatings such as parylene provide a dielectric barrier between the substrate and its environment.

Mineral oil is used extensively inside electrical transformers as a fluid dielectric and to assist in cooling. Dielectric fluids with higher dielectric constants, such as electrical grade castor oil, are often used in high voltage capacitors to help prevent corona discharge and increase capacitance.

Because dielectrics resist the flow of electricity, the surface of a dielectric may retain stranded excess electrical charges. This may occur accidentally when the dielectric is rubbed (the triboelectric effect). This can be useful, as in a Van de Graaff generator or electrophorus, or it can be potentially destructive as in the case of electrostatic discharge.

Piezoelectric materials are another class of very useful dielectrics which are used for transducers and sensors.

Ferroelectric materials often have very high dielectric constants, making them quite useful for capacitors.

## Magnetic Materials

*Classification of dia, para and ferromagnetic materials. Curie Temperature Hysterisis in ferromagnetic materials. Soft and Hard magnetic materials. Applications.*

### Introduction

The materials that can be magnetised are called as magnetic materials

### Magnetic dipoles and magnetic dipole moment

Any two opposite poles separated by distance constitute an magnetic dipole. A magnet is a dipole which has north pole and south pole and the length of the magnet is the distance of separation.

Magnetic dipole moment is the product of magnetic pole strength ( $m$ ) and length of the magnet( $l$ )

$$\mu_m = m.l$$

### Magnetic field intensity (H)

The force experienced by a unit north pole ( of strength 1 Wb) placed at a point in a magnetic field is a measure of the ` field intensity' or `field strength'

### Magnetisation or Intensity of magnetisation (M)

Magnetization may be defined as the process of converting a non magnetic bar into a magnetic bar

### Magnetic Induction Or Flux Density(B)

Magnetic induction or magnetic flux density in an any material is the number of lines of magnetic force passing through unit area perpendicular .  $\text{Wb/m}^2$

$$B = \frac{\phi}{A} = \mu_0 (M + H)$$

### Magnetic Susceptibility ( $\chi$ )

The ratio of the magnetization to the field strength

$$\chi = \frac{M}{H}$$

### Permeability ( $\mu$ )

The ration of the amount of magnetic density B to the applied magnetic field . It is used to measure magnetic lines of forces passing through the material

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

### Origin of Magnetic moment – Bohr Magneton

When ever a charged particle has an angular momentum , it contributes to permanent dipole moment. Consider an hydrogen atom, electron revolving around the nucleus is equal to a current loop. Orbital angular momentum arises due this current loop. The electron spin angular momentum and nuclear spin angular momentum arises due to spin of the electron and nucleus respectively.

There are three angular momentum of an atom

1. Orbital angular momentum of the electron
2. Electron spin angular momentum
3. Nuclear spin angular momentum

Total angular magnetic momentum

### Bohr Magneton

The orbital angular momentum of an electron in an atom can be expressed in terms of atomic unit of magnetic moment called Bohr Magneton.

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

### Classification of the magnetic materials

The magnetic materials are broadly classified in to two types. They are 1. Those atoms or molecules do not have permanent dipole moments and 2. Those atoms or molecules have permanent dipole moments even in the absence of external magnetic field.

Based on the magnetic moments the materials are classified as

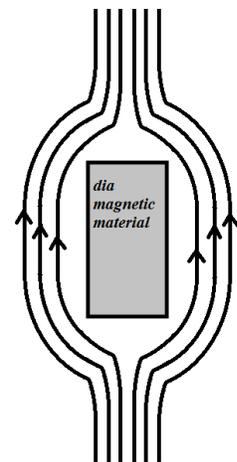
- Diamagnetic materials
- Paramagnetic materials
- Ferromagnetic materials
- Anti ferromagnetic materials
- Ferri magnetic materials

### Diamagnetic materials

Dia magnetic materials has completely filled sub shell electronic structure resultant magnetic moment is zero. There are no permanent dipoles and hence the magnetic effect are small. When a diamagnetic material is placed in a magnetic field, there will be a small induced magnetic moment which always oppose the applied field(accordance with Lenz`s Law). Due to this effect the magnetic lines of forces expelled from the materials.

Mostly the covalent and ionic crystals exhibits the diamagnetic properties. The magnetic susceptibility is small and negative and is independent of temperature.

The examples of diamagnetic materials are 1. Covalent materials such as Si,Ge, diamond, ii) some metals such as copper, silver, gold.

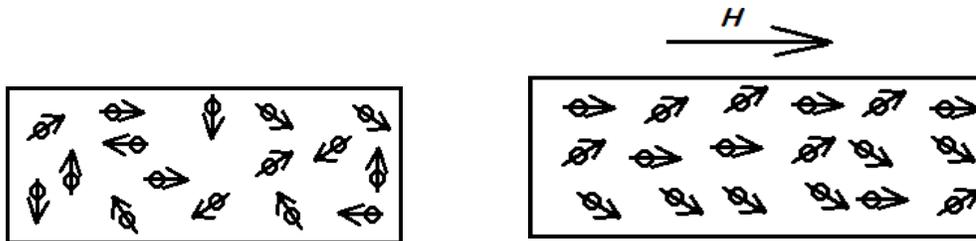


## Para magnetic materials.

Atoms or molecules of paramagnetic materials have permanent magnetic moment oriented in random direction. The magnetic interaction between the dipoles try to align themselves but the thermal agitation disturb the alignment. In paramagnetic materials vector sum of magnetic moments is zero in the absence of field.

When an external magnetic field is applied the partial alignment of permanent atomic magnetic moments occur

When a magnetic field is applied , the individual magnetic moment takes the alignment along the applied field as shown in figure . The magnetization of a paramagnetic material increases with the increase in the applied field. Increase in temperature it reduces the magnetization and destroys the alignment of dipoles with applied field.



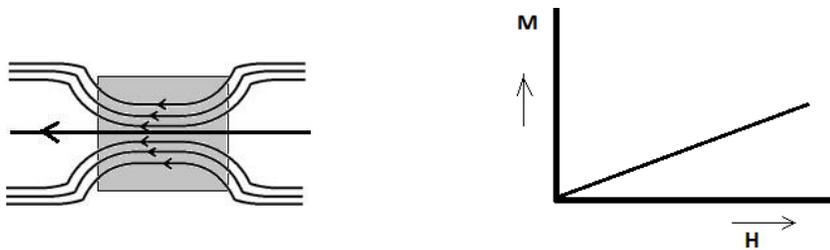
Consider a paramagnetic material placed in non-uniform magnetic field. The paramagnetic materials experience a net magnetic force towards the greater field. The magnetic susceptibility is small and positive and is dependent on temperature. The susceptibility of the magnetic field is given by

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

Where C is the curie temperature and T is the temperature in Kelvin scale.

The magnetization in ferromagnetic material is linear and gets saturated when a large magnetic field is applied at low temperature.

The examples of paramagnetic materials are Mg, gaseous and liquid oxygen , ferromagnetic material ( Fe), and anti-ferromagnetic materials at high temperature and



ferromagnetic material ( $\text{Fe}_3\text{O}_4$ ) at high temperature.

## Ferromagnetic materials

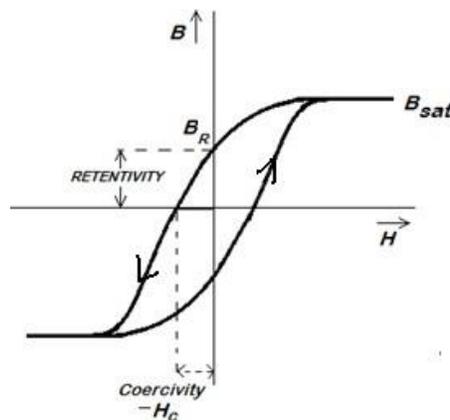
Atoms or molecules of ferromagnetic materials have permanent magnetic moment. In ferromagnetic materials all the dipoles are aligned parallel as shown in the figure if a small value of magnetic field is applied, a large value of magnetization is produced. As the ferromagnetic material have permanent magnetic dipole moment and the susceptibility is positive. The magnetization in ferromagnetic material is non linear and gets saturated when a large magnetic field is applied.



A ferromagnetic materials exhibits two different properties. It behaves as a ferromagnetic material below a certain temperature known as ferromagnetic **curie temperature**. Above the temperature it behaves as a paramagnetic material. In the ferromagnetic region, it exhibits well known curve known as hysteresis curve as shown in the figure.

The susceptibility of a ferromagnetic material above the ferromagnetic curie temperature is given by  $\chi = \frac{C}{T - \theta_f}$

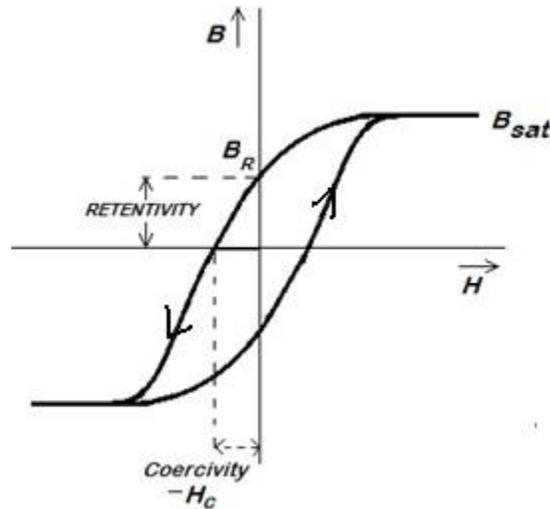
Where C is the Curie constant and  $\theta_f$  is the ferromagnetic Curie temperature. The transition and rare earth metals such as Fe ,Co, Ni ,Gd are the examples of ferromagnetic materials.



## Hysteresis in ferromagnetic materials (B-H curve)

Below the ferromagnetic Curie temperature ( $T < \theta_f$ ) Ferromagnetic material exhibits a well known curve called hysteresis curve. The variation of B( magnetic induction) with H(applied field) can be represented by a closed curve called hysteresis loop or curve. This refers lagging of magnetization behind the magnetising field.

If a magnetic field is increased gradually, the flux density increases and it becomes maximum. The maximum value of flux density is called saturated magnetization. If the field is reversed, the ferromagnetic materials are found to have magnetization in the absence of external field. This is called as retentivity or remanent magnetization ( $B_R$ ) and this property is called as spontaneous magnetization. If the field is further reduced the flux density reduces to zero. The field required in the opposite direction to bring magnetization to zero is called as coercive field or coercivity ( $-H_c$ ). If the field is increased in opposite direction it attains saturation magnetization. If an alternating field is applied a closed loop as shown in the figure is obtained.



According to Weiss, a virgin specimen of ferromagnetic material consists of a number of regions or domains ( $\approx 10^{-6}$  m or above) which are spontaneously magnetized. When a magnetic field is not applied, the direction of spontaneous magnetization varies from domain to domain. The resultant magnetization may hence be zero or nearly zero.

These domains are separated from each other by a wall known as a domain wall or Bloch wall. The domain concept is used to explain the hysteresis property. When an external field is applied, two possible ways of alignment domain growth are possible: one by domain wall motion and the other by rotation of domain wall and domain growth is also reversible. Hysteresis curve is explained by the domain concept.

**Antiferromagnetic materials :** These are the ferromagnetic materials in which equal numbers of opposite spins with the same magnitude such that the orientation of neighbouring spins is in an antiparallel manner are present.

Susceptibility is small and positive and it is inversely proportional to the temperature.

$$\chi = C / (T + \theta)$$

the temperature at which an antiferromagnetic material converts into a paramagnetic material is known as Neel's temperature.

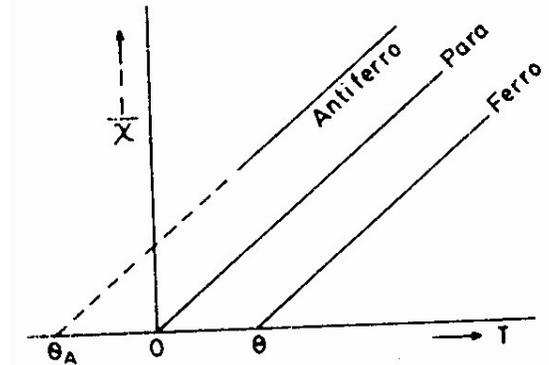
Examples: FeO, Cr<sub>2</sub>O<sub>3</sub>.

**Ferrimagnetic materials:** These are the ferromagnetic materials in which equal no of opposite spins with different magnitudes such that the orientation of neighbouring spins is in antiparallel manner are present.

Susceptibility positive and large, it is inversely proportional to temperature

$$\chi = C / (T \pm \theta) \quad T > T_N \text{ (Neel's}$$

temperature) Examples :  $\text{ZnFe}_2\text{O}_4$ ,  $\text{CuFe}_2\text{O}_4$



## Soft and Hard magnetic materials

### Soft magnetic materials

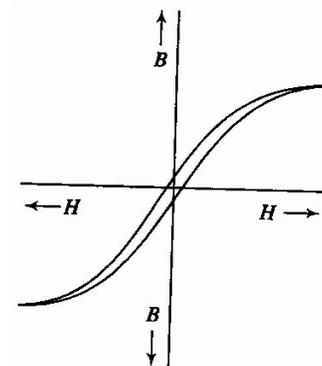
The magnetic materials that are easy to magnetize and demagnetize are called as soft magnetic materials.

Properties:

1. Low remanent magnetization
2. Low coercivity
3. Low hysteresis energy loss
4. Low eddy current loss
5. High permeability
6. High susceptibility

Examples of soft magnetic materials are

- i) Permalloys ( alloys of Fe and Ni)
- ii) Si – Fe alloy
- iii) Amorphous ferrous alloys ( alloys of Fe, Si, and B)
- iv) Pure Iron (BCC structure)



HYSTERESIS CURVE FOR SOFT  
MAGNETIC MATERIAL

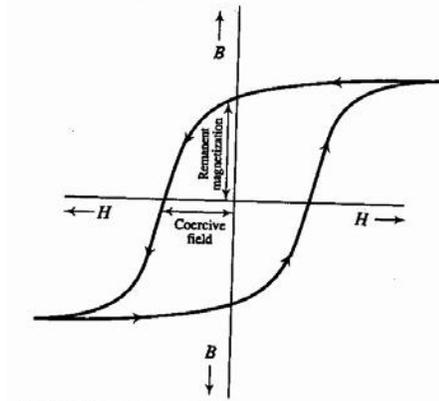
Applications of soft magnetic materials: Mainly used in electro- magnetic machinery and transformer cores. They are also used in switching circuits, microwave isolators and matrix storage of computers.

## Hard magnetic materials

The magnetic materials that are difficult to magnetize and demagnetize are called as hard magnetic materials.

Properties:

1. High remanent magnetization
2. High coercivity
3. High saturation flux density
4. Low initial permeability
5. High hysteresis energy loss
6. High permeability



HYSTERESIS CURVE FOR HARD MAGNETIC MATERIAL

7. The eddy current loss is low for ceramic type and large for metallic type.

Examples of hard magnetic materials are, i) Iron- nickel- aluminum alloys with certain amount of cobalt called Alnico alloy. ii) Copper nickel iron alloys. iii) Platinum cobalt alloy.

Applications of hard magnetic materials: For production of permanent magnets, used in magnetic detectors, microphones, flux meters, voltage regulators, damping devices and magnetic separators.

Hard magnetic materials	Soft magnetic materials
Difficult to magnetize and demagnetize	Easy to magnetize and demagnetize
large hysteresis loop area	small hysteresis loop area
Have large hysteresis loss	Have very low hysteresis loss
The domain wall movement is difficult and it is irreversible in nature	Domain wall movement is relatively easier. Even for small change in the magnetizing field ,magnetization changes by large amount
The coercivity and retentivity are large	The coercivity and retentivity are small
Magnetostatic energy is large	Magnetostatic energy is small.
Small values of permeability and susceptibility	Large values of permeability and susceptibility
Used to make permanent magnets Examples- <i>Iron-nickel-aluminium alloys (alnico)</i> <i>Copper nickel iron (cunife)</i>	Used to make electromagnet Examples- <i>Fe-Si , Ferrous nickel alloys</i> <i>,Ferrites,Garnets</i>

## Sample Questions:

### Dielectric Materials:

1. Explain the phenomenon of electric polarization in dielectric materials?.
2. Describe in brief
  - (a) electronic polarization
  - (b) ionic polarization
  - (c) Orientation polarization
  - (d) Space charge polarisation with diagrams. Also find the total polarizability.
3. Differentiate between polar and nonpolar dielectrics.
4. Drive an expression for internal field in solids and liquids. Or Derive an expression for internal field by Lorentz method?
5. Derive Clausius-Mossoti equation.
6. What are ferroelectric materials? Describe in detail the Ferroelectric hysteresis.
7. Applications of Dielectric materials.
8. Derive the relation between dielectric polarization and dielectric constant?
9. What is its dielectric constant? Explain its importance in dielectric materials?
10. Which of the following properties are typical for dielectrics?
11. Write a note on
  - (a) Ferroelectricity
  - (b) Dielectric constant
  - (c) internal field in solids
12. Discuss the frequency dependence of various polarization processes in dielectric materials.
13. What is dielectric loss? And also explain *Dielectric Breakdown*.
14. Describe the frequency dependence of dielectric constant.
15. Explain the applications of dielectric materials as insulators.

### Magnetic Materials:

1. Define magnetization and show that  $B = \mu_0 (H + M)$
2. Explain the classification of magnetic materials in detail?
3. Give important features of ferromagnetic materials. Explain the hysteresis curve on the basis of domains.
4. What is hysteresis loss? Explain.
5. Distinguish between soft and hard magnets.
6. What is ferromagnetic Curie temperature? Discuss the behaviour of a ferromagnetic material below the Curie temperature.
7. What are ferrites? Explain the magnetic properties of ferrites and mention their industrial applications.
8. Write the importance of hard magnetic materials in engineering applications?
9. What are the applications of soft and hard magnetic materials?

Important formulae:

1. Dipole moment,  $\mu = ql$ .

2. Flux density,  $D = \epsilon_0 \epsilon_r E$ .

3.  $D = \epsilon_0 E + P$ .

4. Dielectric susceptibility,  $\chi = (\epsilon_r - 1)$ .

5. Polarization,  $P = \epsilon_0 (\epsilon_r - 1) E$ ,  $P = N \alpha E$ .

6. Induced dipole moment,  $\mu = \alpha E$ ;  $\mu_e = \alpha_e E$ .

7. Electronic polarizability,  $\alpha_e = \frac{\epsilon_0 (\epsilon_r - 1)}{N}$ .

8. Orientational polarizability,  $\alpha_o = \frac{\mu^2}{3kT}$ .

9. Internal field,  $E = E + \left(\frac{\gamma}{\epsilon_0}\right) P$

10. Lorentz field,  $E_{\text{Lorentz}} = E + \frac{P}{3\epsilon_0}$

11. Clausius - Mossotti relation

$$\frac{(\epsilon_r - 1)}{(\epsilon_r + 2)} = \frac{N \alpha_e}{3\epsilon_0}$$

12. The energy loss in a dielectric material is due to the phase lag of voltage behind the current under a.c. conditions. It is also called

tangent loss given by,  $\tan \delta = \frac{\epsilon_r''}{\epsilon_r'}$ .

13. Curie-Weiss law,  $\epsilon_r = \frac{C}{T - \theta}$  for  $T > T_c$ .

2.  $B = \mu_o \mu_r H$ ,  $\mu_o = 4\pi \times 10^{-7} \text{ H/m}$ .

3.  $\chi = \frac{M}{H}$ .

4.  $B = \mu_o (H + M)$ .

5. Curie Weiss law,  $\chi = \frac{C}{T - \theta}$  for  $T > \theta$ .

## Problems

**An air-filled parallel plate capacitor has a capacitance of 1.5 pF. If the separation between the plates is doubled and wax is inserted between them, the capacitance increases to 3 pF. Compute the dielectric constant of wax.**

Data :

Capacitance when air is dielectric,  $C_1 = 1.5 \text{ pF} = 1.5 \times 10^{-12} \text{ F}$ .

Capacitance when wax is dielectric,  $C_2 = 3 \text{ pF} = 3 \times 10^{-12} \text{ F}$ .

To find :

For wax,  $\epsilon_r = ?$

Solution :

Let the capacitance be  $C_1$  while air is the dielectric,

$$\therefore C_1 = \frac{\epsilon_0 \epsilon_r s}{d}$$

But for air,  $\epsilon_r = 1$ .

$$\therefore 1.5 = \frac{\epsilon_0 \times 1 \times s}{d} \quad \dots\dots(1)$$

When  $d$  is doubled and wax is inserted,

let the capacitance be  $C_2$ .

$$\therefore C_2 = \frac{\epsilon_0 \epsilon_r s}{2d}$$

$$\text{or, } 3 = \frac{\epsilon_0 \epsilon_r s}{2d} \quad \dots\dots(2)$$

Dividing Eq(2) by Eq(1), we have,

$$\frac{3}{1.5} = \frac{\epsilon_0 \epsilon_r s}{2d} \times \frac{d}{\epsilon_0 s}$$

$$\therefore \epsilon_r = 4.$$

$\therefore$  Dielectric constant of wax is 4.

2.

A parallel plate capacitor has an area of  $7.45 \times 10^{-4} \text{ m}^2$  and its plates are separated by a distance of  $2.45 \times 10^{-3} \text{ m}$  across which a potential of  $10 \text{ V}$  is applied. If a material with dielectric constant  $6$  is introduced between the plates, determine the capacitance, the charge stored in each plate, the dielectric displacement  $D$  and the polarization.

Data :

Area of the plates,  $s = 7.45 \times 10^{-4} \text{ m}^2$ .

Distance of separation of the plates,  $d = 2.45 \times 10^{-3} \text{ m}$ .

Applied potential,  $V = 10 \text{ V}$ .

Dielectric constant of the material,  $\epsilon_r = 6$ .

To find :

Capacitance of the capacitor,  $C = ?$ ,

Displacement,  $D = ?$

Charge stored,  $Q = ?$

Polarization,  $P = ?$

Solution :

We have for capacitance of a capacitor,

$$C = \frac{\epsilon_0 \epsilon_r s}{d} = \frac{8.85 \times 10^{-12} \times 6 \times 7.45 \times 10^{-4}}{2.45 \times 10^{-3}},$$

$$= 16.147 \times 10^{-12} \text{ F} = 16.147 \text{ pF}.$$

Charge stored on the plates,

$$Q = CV = 16.147 \times 10^{-12} \times 10,$$

$$= 16.147 \times 10^{-11} \text{ C}.$$

Polarization is given by,

$$P = \epsilon_0 (\epsilon_r - 1) E.$$

But,

$$E = \frac{V}{d}.$$

$\therefore$

$$P = \epsilon_0 (\epsilon_r - 1) \frac{V}{d},$$

$$= \frac{8.85 \times 10^{-12} (6-1) 10}{2.45 \times 10^{-3}}$$

$$= 1.806 \times 10^{-7} \text{ Cm}^{-2}.$$

Displacement  $D$  is given by,

$$D = \epsilon_0 \epsilon_r E = \epsilon_0 \epsilon_r \frac{V}{d} = \frac{8.85 \times 10^{-12} \times 6 \times 10}{2.45 \times 10^{-3}},$$

$$= 2.167 \times 10^{-7} \text{ Cm}^{-2}.$$

$\therefore$  The capacitance, the charge stored, the polarization and the displacement are  $16.147 \text{ pF}$ ,  $16.147 \times 10^{-11} \text{ C}$ ,  $1.806 \times 10^{-7} \text{ Cm}^{-2}$ , and  $2.167 \times 10^{-7} \text{ Cm}^{-2}$  respectively.

3. The dielectric constant of Sulphur is 3.4. Assuming a cubic lattice for its structure, calculate the electronic polarizability for Sulphur.

Given: Sulphur density = 2.07 gm/cc, and atomic weight = 32.07

Given data:

Dielectric constant,  $\epsilon_r = 3.4$ .

Density,  $D = 2.07 \text{ gm/cc} = 2.07 \times 10^3 \text{ kg/m}^3$ .

Atomic weight = 32.07.

Crystal structure of sulphur is cubic.

find :

Electronic polarizability for sulphur,  $\alpha_e = ?$

**Solution :**

Since the crystal structure of sulphur is cubic we can apply Clausius - Mossotti equation,

$$\frac{(\epsilon_r - 1)}{(\epsilon_r + 2)} = \frac{N\alpha_e}{3\epsilon_0}$$

$$\therefore \alpha_e = \frac{3\epsilon_0}{N} \left[ \frac{\epsilon_r - 1}{\epsilon_r + 2} \right] \dots\dots(1)$$

Now,  $N$  the number of atoms/unit volume can be written as,

$$N = \frac{N_A \times 10^3 \times D}{\text{atomic weight}}$$

$$\therefore N = \frac{6.025 \times 10^{26} \times 2.07 \times 10^3}{32.07}$$

$$\therefore N = 3.89 \times 10^{28} / \text{m}^3$$

By substituting the values for various parameters, Eq(1) becomes,

$$\alpha_e = \frac{3 \times 8.854 \times 10^{-12}}{3.89 \times 10^{28}} \left[ \frac{3.4 - 1}{3.4 + 2} \right]$$

$$\therefore \alpha_e = 3.035 \times 10^{-40} \text{ Fm}^2$$

$\therefore$  Electronic polarizability of sulphur is  $3.035 \times 10^{-40} \text{ Fm}^2$ .

4. Find the polarization produced in a dielectric medium of relative permittivity 15 in presence of an electric field of 500 V/m.

Given data:

Relative permittivity,  $\epsilon_r = 15$ .

Strength of electric field,  $E = 500$  V/m.

find :

Polarization,  $P = ?$

We have,

$$\begin{aligned} P &= \epsilon_0(\epsilon_r - 1)E, \\ &= 8.854 \times 10^{-12}(15 - 1)500, \\ &= 6.198 \times 10^{-8} \text{ cm}^{-2}. \end{aligned}$$

**Polarization produced in the medium is  $6.198 \times 10^{-8} \text{ cm}^{-2}$ .**

1. In a magnetic material, the field strength is  $10^6 \text{ Am}^{-1}$ . The magnetic susceptibility of the material is  $0.5 \times 10^{-5}$ . Calculate the intensity of magnetization and the flux density of the material.

$$\chi = \frac{M}{H}$$

$$M = \chi H = 0.5 \times 10^{-5} \times 10^6 = 5$$

$$B = \frac{\phi}{A} = \mu_0(M + H)$$

$$= 4\pi \times 10^{-7}(5 + 10^6)$$

$$= 1.257 \text{ Wbm}^{-2}$$

2. If a magnetic field of  $1800 \text{ Am}^{-1}$  produces a magnetic field  $3 \times 10^{-5} \text{ Wb}$  in an iron bar of cross sectional area  $0.2 \text{ cm}^2$ , Calculate permeability.

$$B = \frac{\phi}{A} = 1.5 \text{ Wbm}^{-2}$$

$$B = \mu_0 \mu_r H$$

$$\mu_r = \frac{B}{H\mu_0} = \frac{1.5}{4\pi \times 10^{-7} \times 1800} = 663.14$$

3. Calculate the saturation magnetization for Ni ferrite. The lattice parameter of a cubic unit cell of Ni ferrite is  $0.835 \text{ nm}$  and the magnetic moment per unit cell is  $18.4 \mu_B$ .

$$(\mu_B = 9.27 \times 10^{-24})$$

$$M = \frac{\text{Magnetic moment}}{\text{volume}} = \frac{18.4 \times 9.27 \times 10^{-24}}{(0.835 \times 10^{-9})^3} = 2.929 \times 10^5$$

## Introduction:

### Magnetism

A substance that attracts pieces of iron (or) steel is called “Magnet”. This property of a substance is called “magnetism.

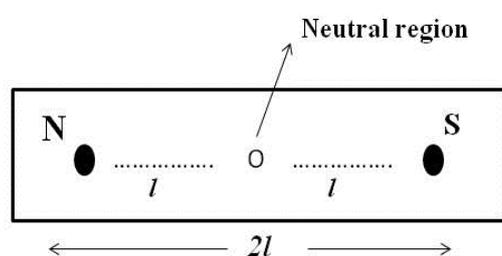
### Magnetic Poles:

When a bar magnet is dipped in a heap of iron filings and taken out, it is seen that maximum amount of iron filings are seen to cling to the magnet at the two ends of the magnet. Practically no iron filings cling in the middle. The regions of the magnet at which maximum amount of iron filings cling are called poles of the magnet. ***Poles of magnet are regions near the two ends of a magnet with maximum power of attraction.*** The strength of the pole is called **pole strength** denoted by  $m$ . The **S.I. unit of pole strength is Ampere Meter**.

The distance between two magnetic poles is called “magnetic length” ( $2l$ ).

### Magnetic Dipole:

- Magnetic dipoles are found to exist in magnetic materials, analogous to electric dipoles.
- Two equal and opposite charges separated by a small distance is called an electric dipole. Similarly a north pole and south pole separated by a small distance  $2l$  (**magnetic length**) constitute a magnetic dipole.
- *For example:* A bar magnet, a compass needle etc. are the magnetic dipoles. And also a current loop behaves as a magnetic dipole.



**Fig : Magnetic dipole**

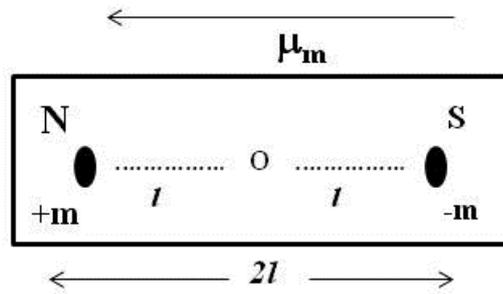
### Magnetic Dipole Moment:

The behavior of magnetic dipole is described by the magnetic dipole moment.

#### (a) In the case of bar magnet:

It is defined as the product of pole strength ( $m$ ) and magnetic length ( $2l$ ).

$$\vec{\mu}_m = m (2l)$$



**Fig : Magnetic dipole moment**

It is a vector quantity. It is directed from South Pole to North Pole.  
 The S.I. Unit of magnetic dipole moment: Ampere – meter<sup>2</sup> (A-m<sup>2</sup>).

**(b) In the case of current loop:**

A current carrying loop behaves as a magnetic dipole.  
 Consider a current carrying conductor loop of wire as shown fig. The current (I) establishes a magnetic field around the loop. By right hand palm rule, the upper face of the loop acts as a S- pole and the lower face act as N- pole.

The magnitude of dipole moment of current loop ( $\mu_m$ ) is

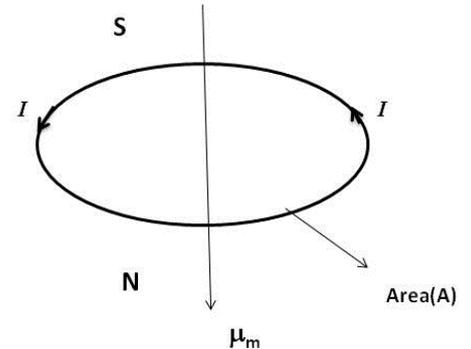
- (i) Directly proportional to current (I) through the loop.
- (ii) Directly proportional to the area of cross –section (A).

$$\mu_m \propto I.A$$

$$\mu_m = K IA$$

$$\mu_m = IA$$

Where K is a proportionality whose value is one

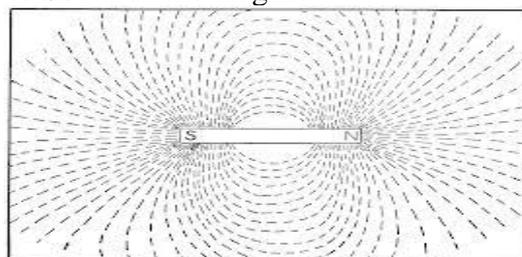


**Fig : Current carrying conductor loop**

**Magnetic Field:**

The space surrounding a magnet where magnetic force is experienced is called a magnetic field.

A magnetic field can be represented by drawing lines called “magnetic lines of force”. The lines go from North to South on the magnet.



**Fig: Magnetic field.**

### Magnetic Flux:

A group of magnetic lines of force is called “magnetic flux”.

The symbol for magnetic flux is  $\Phi$  (phi).

The SI unit of magnetic flux is the Weber (Wb).

One Weber is equal to  $1 \times 10^8$  magnetic field lines.

### Magnetic Flux Density:

Magnetic flux density is the amount of magnetic flux per unit area of a section, perpendicular to the direction of flux.

$$\text{Magnetic flux density (B)} = \frac{\text{Magnetic flux (Weber)}}{\text{Area (m}^2\text{)}}$$

$$B = \frac{\Phi}{A} \text{ Tesla}$$

### Magnetization:

Magnetization in magnetic field is analogous to polarization of dielectric material in electrostatic field.

The process of converting a non-magnetic material into a magnetic material is known as “magnetization”.

### Intensity of Magnetization ( I or M)

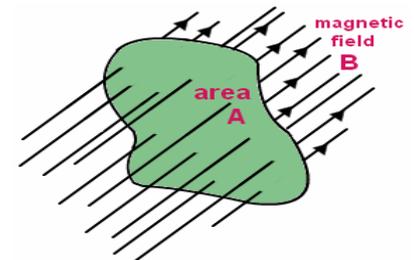
When a material medium is placed in a magnetic field, it gets magnetized. To magnetize a material medium is to create magnetic dipole moments.

The magnetic dipole moment per unit volume of the material is called the intensity of magnetization I (or simply magnetization).

$$I = \frac{\text{Magnetic dipole moment}(\mu_m)}{\text{Volume (V)}} = \frac{\text{Length of magnet (2l) X Pole Strength (m)}}{\text{Length of Magnet (2l) X Area of cross -section (A)}}$$

$$= \frac{\text{Pole Strength (m)}}{\text{Area of Cross Section (A)}}$$

The S.I. Unit of magnetization is ampere / meter



### Magnetic Field Strength (H):

The ability of magnetic field to magnetize a material medium is called its magnetic intensity or field strength. It is denoted by **H**.

The S.I. Unit of magnetic field strength is ampere / meter.

### Magnetic Susceptibility ( $\chi_m$ ):

The word Susceptibility comes from the Latin word “susceptible” means the easily affected

The magnetic susceptibility of a material medium indicates how easily a material medium can be magnetized in the presence of magnetic field..

The intensity of Magnetization is directly related to the applied field strength H.

$$M \propto H$$
$$M = \chi_m H$$

$$\text{Magnetic Susceptibility } (\chi_m) = \frac{M}{H}$$

Therefore; the magnetic susceptibility of a material is defined as the ratio of intensity of magnetization (I) developed in the material to the applied magnetic field (H).

**Magnetic Permeability ( $\mu$ ):**

- It is the natural property of material.
- In Latin, *per* means *through* and *meare* means *to pass*.
- It is defined as the ability of the material to permit the passage of magnetic lines of force through it.
- The Magnetic induction B is proportional to the applied Magnetic field intensity H.

$$B \propto H$$

$$B = \mu H$$

$$\text{Magnetic Permeability } (\mu) = \frac{B}{H}$$

Where “ $\mu$ ” is the permeability of a medium.

For vacuum,

$$B = \mu_0 H$$

Where  $\mu_0$  is the proportionality constant and is also called permeability of the free space and its value is  $4\pi \times 10^{-7} \text{ H m}^{-1}$ .

**Relative permeability ( $\mu_r$ ):**

The ratio of permeability of medium to the permeability of free space is called relative permeability  $\mu_r$  of the medium

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

$\mu_r = 1$  for vacuum. It has no units.

**The Relation between Relative Permeability and Magnetic Susceptibility:**

When a magnetic material is magnetized by placing it in a magnetic field, the resultant field inside the material is the sum of the field due to the magnetization of the material and the original magnetizing field. The resultant field is called magnetic induction or magnetic flux density **B**.

$$B = \mu_0 H + \mu_0 M$$

$$B = \mu_0 (H + M)$$

$$\mu H = \mu_0 (H + M) \quad (B = \mu H \text{ and } \mu = \mu_0 \mu_r)$$

$$\mu_0 \mu_r H = \mu_0 \left(1 + \frac{M}{H}\right)$$

$$\mu_r = (1 + \chi_m)$$

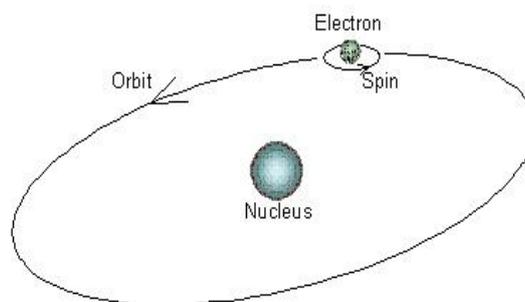
This is the relation between Relative Permeability and Magnetic Susceptibility.

**Origin of Magnetism:**

Magnetism originates from magnetic dipole moment. This magnetic dipole moment arises due to the rotational motion of charged particles.

According to modern view:

- All substances are made of atoms or molecules. An atom which consists of ‘+’vely charged nucleus at the centre and negatively charged electrons revolving around the nucleus in different orbits. This motion of electrons is called orbital motion as shown in fig. The orbiting electrons constitute tiny current loops. These loops behave as the magnetic dipoles.
- The orbital motion of electrons around the nucleus gives rise to the orbital magnetic dipole moment ( $\mu_{\text{orbit}}$ ).
- The electrons also rotate around their own axes. This motion of electrons is called spin motion as shown fig. The spinning motion of electrons around their axes gives rise to the spin magnetic dipole moment ( $\mu_{\text{spin}}$ ).
- The motion of the protons and neutrons within the nucleus also contributes to the total magnetic moment ( $\mu_{\text{nucleus}}$ ). But the magnitude of the nuclear magnetic moment is (about  $10^{-3}$  times) very small compared with the magnetic moment of electron and is usually neglected.



**Fig: Motion of electron**

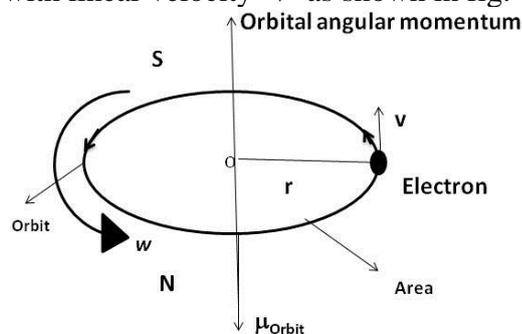
**Orbital magnetic dipole moment of electron ( $\mu_{\text{orbit}}$ ):**

The magnetic dipole moment arises due to the orbital motion of electrons around the nucleus is called orbital magnetic dipole moment ( $\mu_{\text{orbit}}$ ).

**Proof:**

$$\mu_{\text{Orbit},z} = -\mu_B \cdot m_l$$

Let us consider an electron charge  $e$  revolving around the nucleus in a circular orbit of radius ‘ $r$ ’ with linear velocity ‘ $v$ ’ as shown in fig.



**Fig : Orbital motion of electron**

The revolving electron in circular orbit establishes a current is given by

$$I = \frac{\text{Charge of electron}}{\text{time period}} = \frac{-e}{T} \longrightarrow (1)$$

Where 'T' is the time taken by the electron to make one revolution around the nucleus

$$\text{i.e., } T = \frac{2\pi}{\omega} \longrightarrow (2)$$

Where 'ω' is the angular frequency of the electron

But relation between linear velocity 'v' and angular velocity can be written as

$$v = r \omega$$

$$\text{and } \omega = \frac{v}{r} \longrightarrow (3)$$

Substituting the equation (3) in (2),

$$T = \frac{2\pi r}{v} \longrightarrow (4)$$

Further, substituting the equation (4) in (1),

$$I = \frac{-ve}{2\pi r} \longrightarrow (5)$$

The current 'I' establishes a magnetic field around the circular orbit, so that the upper surface acts as South Pole and the lower surface acts as North Pole.

The Area of the orbit is  $A = \pi r^2 \longrightarrow (6)$

Then the corresponding magnetic dipole moment is given by

$$\mu_{\text{Orbit}} = IA$$

$$= \frac{-ve}{2\pi r} \times \pi r^2$$

$$= \frac{-evr}{2} \longrightarrow (7)$$

Dividing and multiplying the equation (7) by the mass 'm' of electron.

$$\mu_{\text{Orbit}} = \frac{-evr}{2} \times \frac{m}{m}$$

$$= \frac{-e(mvr)}{2}$$

$$= \frac{2m}{-e} \frac{L}{2m} \quad (\text{But } L = mvr)$$

$$\mu_{\text{Orbit}} = \frac{-e}{2m} \vec{L} \quad (\text{Orbital angular momentum})$$

The -ve sign indicates that the orbital angular momentum and orbital magnetic dipole moment are in opposite directions.  $\longrightarrow$

*An electron has an intrinsic orbital angular momentum (  $\vec{L}$  ) itself cannot be measured. However, its component along any axis can be measured.*

Let us assume that the component of orbital angular momentum (  $\vec{L}$  ) is measured along the z- axis of a coordinate system. Then the measured component  $L_z$  can have only the values is given by

$$L_z = m_l \frac{h}{2\pi}$$

Where  $m_l$  is called orbital magnetic quantum number =  $0, \pm 1, \pm 2, \pm 3 \dots$

The orbital magnetic dipole moment ( $\mu_{\text{Orbit}}$ ) of electron itself also cannot be measured. Only; its component along any axis can be measured.

Let us assume that the component of orbital magnetic dipole moment ( $\mu_{\text{Orbit}}$ ) of electron is measured along the z- axis of a coordinate system. Then the measured component  $\mu_{\text{Orbit}, z}$  can have only the two values is given by

$$\mu_{\text{Orbit}, z} = \frac{-e}{2m} L_z$$

$$\mu_{\text{Orbit}, z} = - \left( \frac{e}{2m} \right) m_l \frac{h}{2\pi}$$

$$\mu_{\text{Orbit}, z} = - \left( \frac{eh}{4\pi m} \right) m_l$$

$$\mu_{\text{Orbit}, z} = - \mu_B \cdot m_l$$

Where  $\mu_B = \frac{eh}{4m\pi}$  is known as Bohr magneton and its value is  $9.27 \times 10^{-24} \text{ A}\cdot\text{m}^2$ .

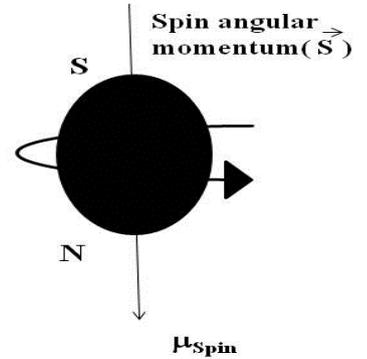


Fig: Spin motion of electron

### Spin magnetic dipole moment of electron ( $\mu_{\text{spin}}$ ):

The magnetic dipole moment arises due to its spin motion is called spin magnetic moment ( $\mu_{\text{spin}}$ ) and is given by

$$\mu_{\text{Spin}} = -g \left( \frac{e}{2m} \right) \vec{S} \text{ (Spin angular momentum)}$$

The - ve sign indicates that the spin angular momentum and spin magnetic dipole moment are in opposite directions.

Where  $g$  is called land's  $g$  factor or Spectroscopic splitting factor

$$g = \frac{1+J(J+1)+S(S+1)-L(L+1)}{J(J+1)}$$

$g_l=1$  for orbital motion

$g_s=2$  for spin motion

An electron has an intrinsic spin angular momentum ( $\vec{S}$ ) itself cannot be measured.

However, its component along any axis can be measured..  $\rightarrow$

Let us assume that the component of spin angular momentum ( $S$ ) is measured along the  $z$ - axis of a coordinate system. Then the measured component  $S_z$  can have only the values is given by

$$S_z = m_s \frac{h}{2\pi}$$

Where  $m_s$  is called magnetic spin quantum number =  $\pm \frac{1}{2}$

$m_s = +\frac{1}{2}$  for spin up and

$m_s = -\frac{1}{2}$  for spin down

The spin magnetic dipole moment ( $\mu_{\text{spin}}$ ) of electron itself also cannot itself be measured. Only; its component along any axis can be measured. Let us assume that the component of spin magnetic dipole moment ( $\mu_{\text{spin}}$ ) of electron is measured along the  $z$ - axis of a coordinate system. Then the measured component  $\mu_{\text{spin}, z}$  can have only the two values is given by

$$\mu_{\text{Spin}, z} = -g \left( \frac{e}{2m} \right) S_z$$

$$\mu_{\text{Spin}, z} = -g \left( \frac{e}{2m} \right) m_s \frac{h}{2\pi}$$

$$\mu_{\text{Spin}, z} = - 2 \left( \frac{eh}{4\pi m} \right) m_s$$

$$\mu_{\text{Spin, z}} = -2 (\mu_B) m_s$$

Where  $\mu_B = \frac{eh}{4m\pi}$  is known as Bohr magneton and its value is  $9.27 \times 10^{-24} \text{ A}\cdot\text{m}^2$ .

### Nuclear spin magnetic dipole moment ( $\mu_{\text{Nuclear}}$ ):

The atomic nucleus contains protons and neutrons. They have intrinsic spin. The spin motion of the protons and neutrons within the nucleus also contributes to the total spin magnetic dipole moment and is given by

$$\mu_{\text{nuclear, spin}} = \frac{eh}{4\pi M_N} = 5.525 \times 10^{-27} \text{ A}\cdot\text{m}^2$$

Where  $M_N$  is the Mass of the proton

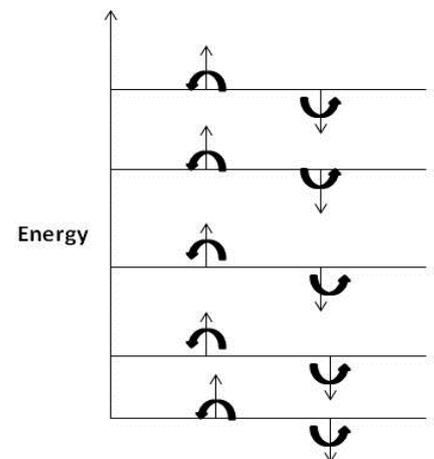
But the magnitude of the nuclear magnetic dipole moment is (about  $10^{-3}$  times) very small compared with the magnetic dipole moment of electron and is usually neglected.

*Therefore, the magnetism mainly arises due to the orbital and spin magnetic dipole moments of electron.*

### Classification magnetic materials:

Magnetic materials are classified based on presence or absences of the permanent magnetic dipoles in a material. They are

1. Dia magnetic material
2. Para magnetic material
3. Ferro magnetic material
4. Anti Ferro magnetic material and
5. Ferri magnetic material



### Diamagnetic materials:

Those materials which when placed in a magnetic field are weakly or feebly magnetized in a direction opposite that of the applied magnetic field are called diamagnetic materials

### Examples:

Bismuth, Copper, Zinc, Gold, Water, etc

### Cause of diamagnetism:

In the Diamagnetic materials, there exist paired electrons, so the spins in two opposite directions are equal and hence magnetic dipole moments cancel with each other. i.e., the resultant magnetic dipole moment is equal to zero.

Therefore, most of these materials do not have magnetism in the absence of magnetic field.

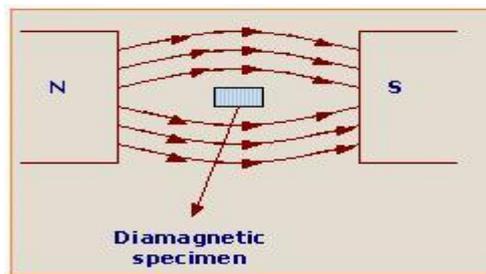
### Effect of external magnetic field:

- a) In the absence of external magnetic field, the atoms/molecule/ions of the diamagnetic substance have no net magnetic dipole moment. Hence, the material does not exhibit diamagnetism

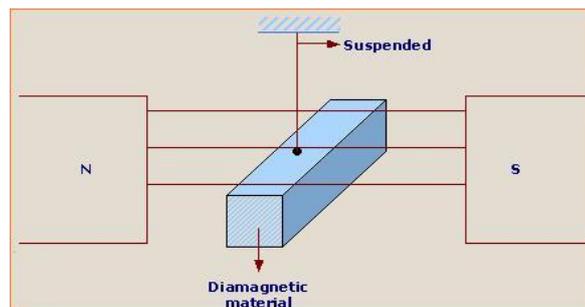
- b) When a diamagnetic material is placed in an external magnetic field, currents are induced in the current loops of atom/molecule/ion according to Faraday's law of electromagnetic induction. According to Lenz's law, these currents give rise to a magnetic field which opposes the applied magnetic field. Hence, the induced magnetic moments of atoms/molecule/ions are opposite to the applied magnetic field.

**Properties:**

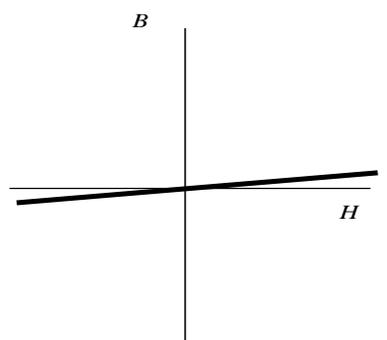
- They don't possess permanent magnetic dipole moment.
- When a diamagnetic material is placed in a magnetic field, it is feebly magnetized in a direction opposite to that of the applied magnetic field.
- When a diamagnetic material is placed in a magnetic field, the magnetic lines force prefers to pass through the surroundings air rather than through the diamagnetic magnetic material.



- The magnetic flux density inside is small than that in the free space. Hence the relative permeability  $\mu_r < 1$ .
- The magnetic susceptibility ( $\chi_m$ ) is negative and small.
- The magnetic susceptibility ( $\chi_m$ ) is independent of temperature.
- When a rod of diamagnetic material is suspended freely in a uniform magnetic field, the rod comes to rest with its axis perpendicular to the direction of the applied field.



- The B-H curve of diamagnetic material as shown in fig.



### **Para magnetic materials:**

Those materials which when placed in a magnetic field are weakly or feebly magnetized in the direction of the applied magnetic field are called Para magnetic materials.

#### **Examples:**

Aluminum, platinum, copper sulphate( $\text{CuSO}_4$ ), manganese, chromium etc.

#### **Cause of paramagnetism:**

In the case of paramagnetic materials, the spins in two opposite directions will not be equal. There exist some unpaired electrons which gives rise to spin magnetic dipole moment.

Hence the resultant magnetic dipole moment will not be equal to zero. i.e., they possess permanent magnetic dipole moment.

#### **Effect of external magnetic field:**

- c) In the absence of external magnetic field, the dipoles of the paramagnetic material are randomly oriented and, therefore, the net magnetic dipole moment of the material is zero. Hence, the material does not exhibit paramagnetism.
- d) When a paramagnetic material is placed in an external magnetic field, the magnetic dipoles are partially aligned in the direction of the applied magnetic field. Therefore, the material is weakly or feebly magnetized in the direction of the applied magnetic field.

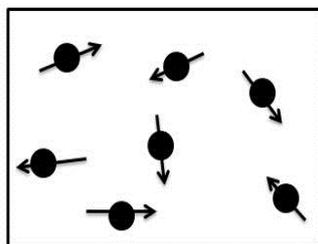


Fig: In the absence of external magnetic field ( $H=0$ )

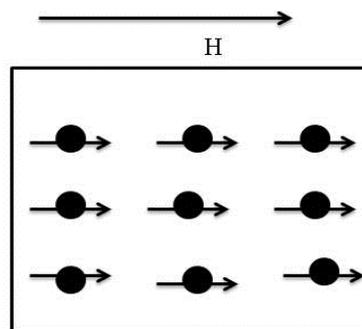
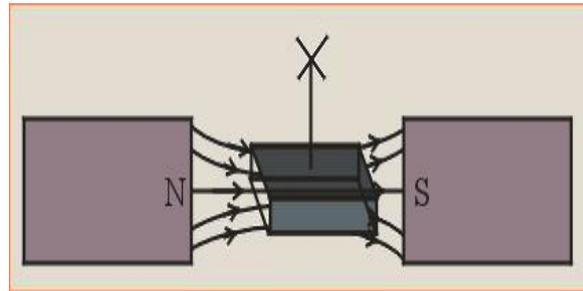


Fig: In the presence of external magnetic field

### **Properties:**

- They possess permanent magnetic dipole moment.
- When a paramagnetic material is placed in a magnetic field, it is feebly or weakly magnetized in the direction of applied magnetic field.

- When a paramagnetic material is placed in a magnetic field, the magnetic lines force prefers to pass through the paramagnetic magnetic material rather than air.

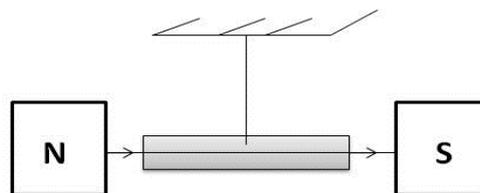


- The magnetic flux density inside is greater than that in the free space. Hence the relative permeability  $\mu_r > 1$ .
- The magnetic susceptibility ( $\chi_m$ ) is positive and small.
- The magnetic susceptibility ( $\chi_m$ ) is inversely proportional to the temperature.

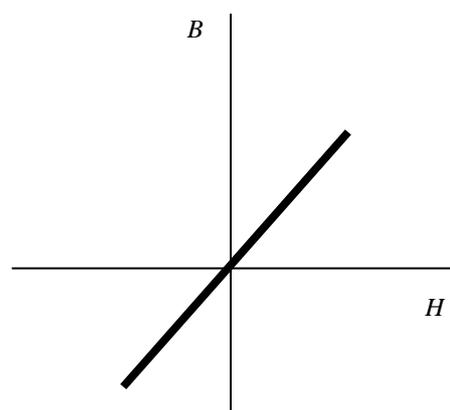
$$\chi_m = \frac{C}{T - \theta_C} \text{ (Curie-Weiss law)}$$

Where C  $\rightarrow$  Curie constant  
 T  $\rightarrow$  Absolute temperature and  
 $\theta_C$   $\rightarrow$  Curie temperature

- When the temperature is less than the Curie temperature, paramagnetic materials becomes diamagnetic material.
- When a rod of paramagnetic material is suspended freely in a uniform magnetic field, the rod comes to rest with its axis parallel to the applied field.



- The B-H curve of Para magnetic material as shown in fig.



### **Ferro magnetic materials:**

Those materials which when placed in a magnetic field are strongly magnetized in the direction of the applied magnetic field are called Ferro magnetic materials.

### **Examples:**

Iron, Steel, Nickel, Cobalt, etc

### **Cause of Ferro magnetism:**

- In a Ferro magnetic material, the number of unpaired electrons is more and most of the magnetic dipole moments align parallel to each other even in the absence of magnetic field..Hence they possess permanent magnetic dipole moment even in the absence of magnetic field.
- In Ferro magnetic materials, atoms grouped into regions called *domains*, instead of acting independently like paramagnetic materials.

***The region of space over which the magnetic dipole moments are aligned is called domain.***

A typical domain contains  $10^{17}$  to  $10^{21}$  atoms and occupies a volume of  $10^{-12}$  to  $10^{-8}$  m<sup>3</sup>.

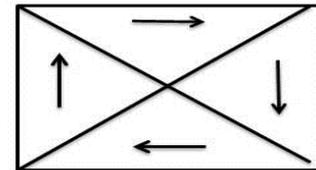
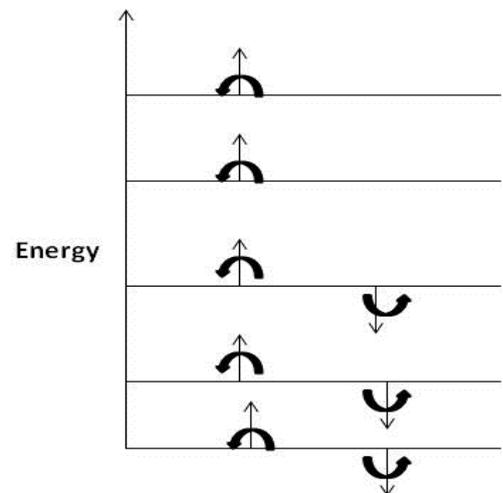


Fig: Without field

### **Effect of external magnetic field:**

- a) In the absence of external magnetic field, the domains of a ferromagnetic material are randomly oriented. In other words, within the domain, all magnetic dipole moments are aligned, but the direction of alignment varies from domain to domain. The result is that there is no net magnetic dipole moment. Therefore, a Ferro magnetic material does not exhibit magnetism in the normal state.
- b) When a Ferro magnetic material is placed in an external magnetic field, a net magnetic dipole moment develops. This can occur in two ways:
  - i) By the movement of domain walls
  - ii) By the rotation of domain walls.

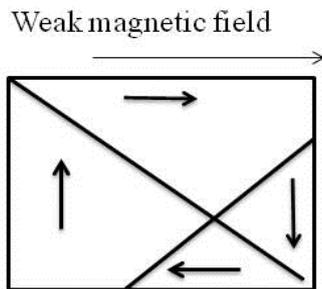


#### **i) By the movement of domain walls:**

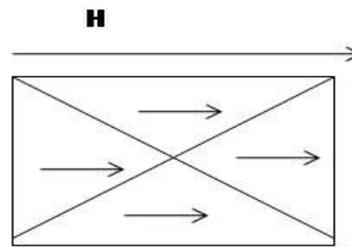
- The movement of domain walls takes place in weak magnetic fields.
- Due to weak magnetic field applied to the material the magnetic dipole moments increases and hence the boundary of domains displaced, so that the volume of the domains changes as shown in fig.

#### **ii) By the rotation of domain walls**

- The rotation of domain wall takes place in strong magnetic fields.
- Due to strong magnetic field applied to the material the magnetic dipole moments increases enormously and hence the domains rotate, so that the magnetic dipole moments are aligned in the direction of applied magnetic field as shown in fig.



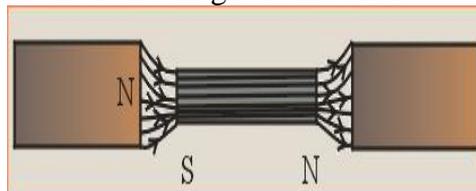
**Fig: Displacement of domain walls**  
With weak magnetic field



**Fig: Rotation of domain walls in strong magnetic field**

**Properties:**

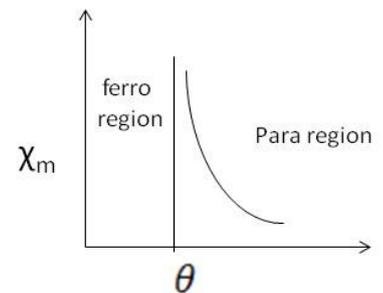
- They possess permanent magnetic dipole moment.
- When a Ferro magnetic material is placed in a magnetic field, it is strongly magnetized in the direction of applied magnetic field.
- When a Ferro magnetic material is placed in a magnetic field, the magnetic lines force tend to crowd into the Ferro magnetic material.



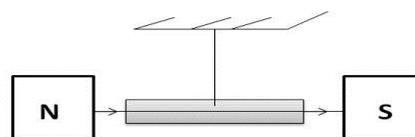
- The magnetic flux density inside is very greater than that in the free space. Hence the relative permeability  $\mu_r \gg 1$ .
- The magnetic susceptibility ( $\chi_m$ ) is positive and very high.
- The magnetic susceptibility ( $\chi_m$ ) is inversely proportional to the temperature.

$$\chi_m = \frac{C}{T - \theta_c} \text{ (Curie-Weiss law)}$$

Where  $C \rightarrow$  Curie constant  
 $T \rightarrow$  Absolute temperature and  
 $\theta_c \rightarrow$  Curie temperature



- When the temperature is greater than the Curie temperature, ferromagnetic materials becomes Para magnetic material.
- When a rod of Ferro magnetic material is suspended freely in a uniform magnetic field, it quickly aligns itself in the direction of the applied magnetic field.



**Classification of Ferro magnetic materials:**

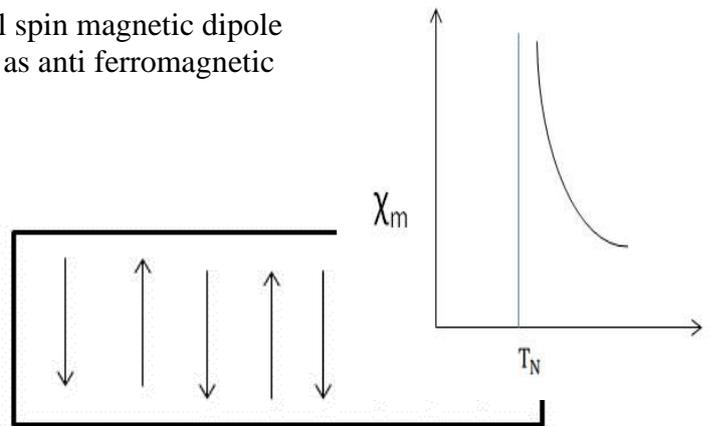
Depending upon the spin orientation of the electrons, ferromagnetic materials are classified into two types, they are 1. Antiferromagnetic materials 2. Ferri magnetic materials

**Antiferromagnetic materials:**

The materials which consist of anti parallel spin magnetic dipole moment with same magnitudes are known as anti ferromagnetic materials.

**Examples:**

- Ferrous oxide (FeO),
- Manganese oxide (MnO<sub>4</sub>),
- Manganese sulphide MnS),
- Chromium Oxide (Cr<sub>2</sub>O<sub>3</sub>),
- Ferrous Chloride (FeCl<sub>2</sub>) etc



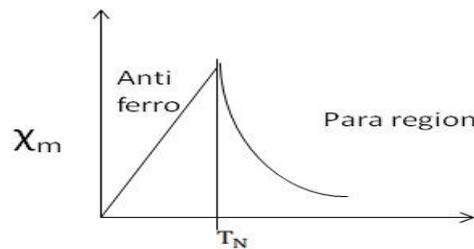
**Properties:**

- In this materials spin magnetic dipole moments are aligned in anti parallel manner.
- The magnetic susceptibility is very small and positive
- The magnetic susceptibility is inversely proportional to temperature. The variation of susceptibility with temperature is shown in fig.

$$\chi_m = \frac{C}{T \pm \theta_c}$$

Where C → Curie constant  
 T → Absolute temperature and  
 θ<sub>c</sub> → Curie temperature

χ<sub>m</sub> is increases gradually with temperature and attains a maximum value at Neel temperature(T<sub>N</sub>) and then decreases with increase in temperature.

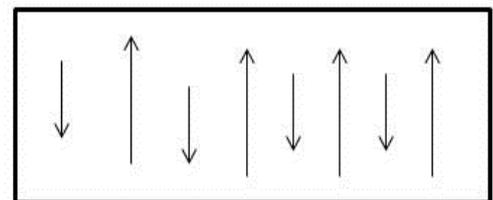


**Ferrimagnetic materials:**

The materials which consist of anti parallel magnetic dipole moments of different magnitudes are known as ferrimagnetic materials.

**Examples:**

- Ferrites-general formula: Me<sup>+2</sup> Fe<sup>2+</sup>O<sub>4</sub>
- Where Me<sup>+2</sup> =divalent metal ions(Zn,Cu,Ni).



**Properties:**

- In this materials spin magnetic dipole moments of different magnitudes are aligned in anti parallel manner.

- The magnetic susceptibility is very high and positive
- The magnetic susceptibility is inversely proportional to temperature. The variation of susceptibility with temperature is shown in fig.

$$\chi_m = \frac{C}{T \pm \theta_C}$$

Where C → Curie constant  
 T → Absolute temperature and  
 $\theta_C$  → Curie temperature

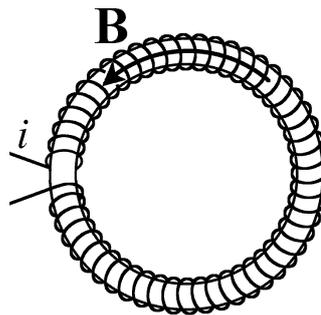
### HYSTERISIS:-

When a Ferro magnetic substance (e.g. iron) is subjected to a cycle of magnetization, it is found that flux density B in the material lags behind the applied magnetizing force H. This phenomenon is known as hysteresis.

The term hysteresis is derived from the Greek word hysterein meaning to lag behind.

#### Hysteresis loop:

- If a piece of ferromagnetic material is subjected to one cycle of magnetization, the resultant B-H curve is a closed loop “a b c d e f a” is Called hysteresis loop.
- Consider an iron-cored toroid carrying current I. If N is the total number of turns and  $\ell$  the length of toroid, then magnetizing force is  $H = NI/\ell$ . The value of H can be changed by varying current in the coil.

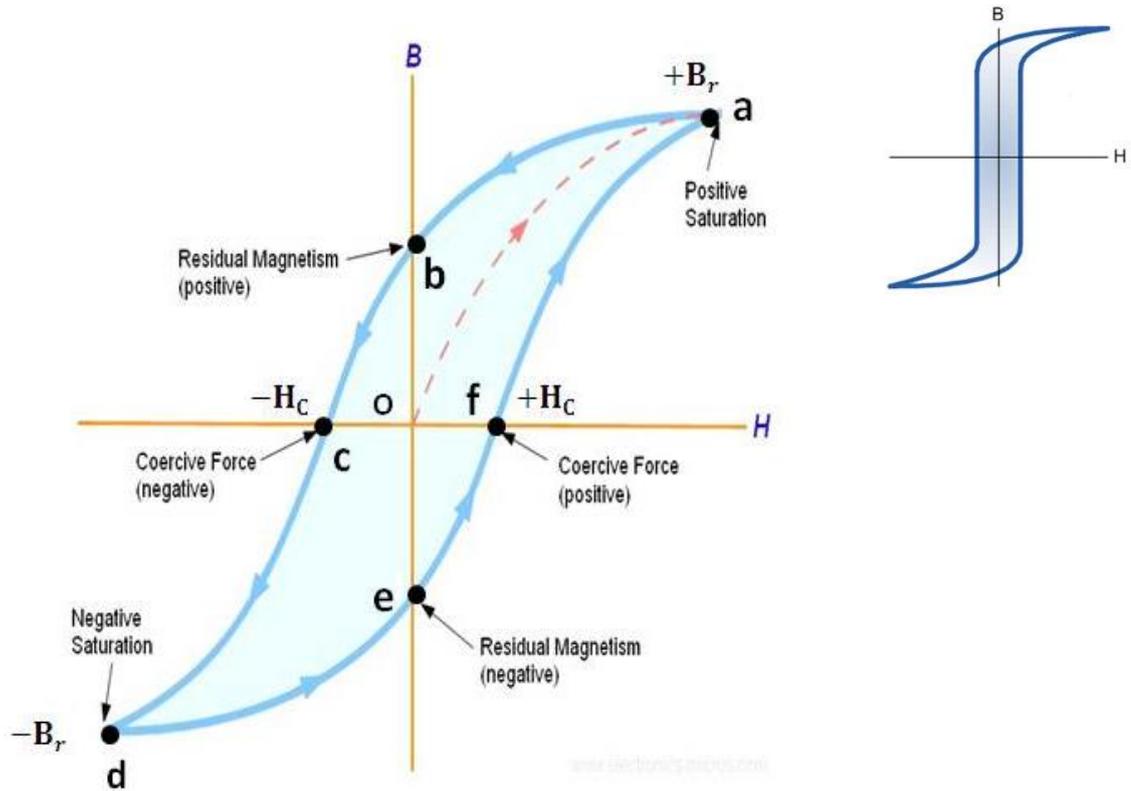


**Fig: Toroid**

- To start with, the toroid is unmagnetised and its situation is represented by point
- in fig. As H is increased (by increasing current I), B increases along oa and reaches its saturation value  $B_{max}$  at a. At this stage, all the domains are aligned.
- If now H is gradually reduced by decreasing the current in the toroid, it is found that curve follows the path ab instead of ao. At point b,  $H=0$  but flux density in the material has a finite value  $+B_r$  (=ob) called *residual flux density*. It is also called **remanence** or **retentivity**. Note that B lags behind H. This effect is called *hysteresis*.
- In order to reduce flux density in the material to zero, it is necessary to apply H in the reverse direction. This can be done by reversing the current I the toroid. When H is gradually increased in the reverse direction, the curve follows the path bc. At point c,  $B=0$  and  $H = -H_C$ . The value of H needed to wipe out residual magnetism is called coercive force ( $H_C$ ).
- Now H is further increased in the reverse direction until point d is reached where the sample is saturated in the reverse direction ( $-B_{max}$ ). If H is now reduced to zero point e is reached and the sample again retains magnetic flux density ( $-B_r$ ). The remaining part of the loop is obtained by increasing current to produce H in the original direction. The curve “a b c d e f a” is called hysteresis loop. Thus

hysteresis loop results because the domains do not become completely unaligned when  $H$  is made zero. The area enclosed by the hysteresis loop represents loss in energy. This energy appears in the material as heat.

- vi. Based on the area of the hysteresis loop, the magnetic materials are classified into soft and hard magnetic materials.



**Fig: B-H Curve**

**Soft magnetic materials:-**

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

**Properties:**

- They can be easily magnetized and demagnetized and hence they show high values of susceptibility and permeability.
- Movement of domain wall is easy and hence even for small applied field large magnetization occurs.
- The nature of hysteresis loop is very narrow
- The hysteresis loop area is very small hence the hysteresis loss is also small as shown in fig.
- The coercivity and retentivity values are small
- These materials are free from irregularities or impurities or imperfections

**Examples:**

Fe- Si alloys, Ni-Fe alloys, Fe-Co alloys, Ferrites and Garnets etc

- **Applications:**

- They are used in switching devices, electromagnets,
- They are used in matrix storage of computers.
- They are used in motors, relays and sensors
- They are used to make the temporary magnets.

**Hard magnetic materials:-**

The materials which can't be easily magnetized and demagnetized are called hard magnetic materials.

**Properties:**

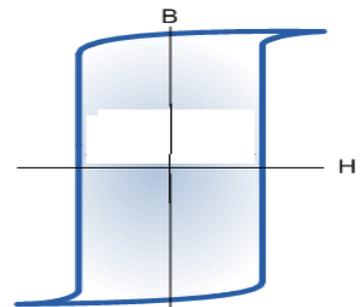
- They can't be easily magnetized and demagnetized and hence they show low values of susceptibility and permeability.
- Movement of domain wall is not easy due to presence of impurities and hence large magnetic field is required for magnetization
- The nature of hysteresis loop is very broad.
- The hysteresis loop area is large hence the hysteresis loss is also large as shown in fig.
- The coercivity and retentivity values are high
- These materials are have irregularities or impurities or imperfections

- **Examples:**

Carbon steel, tungsten steel, chromium steel,  
Cu-Ni-Fe alloys  
Cu-Ni-Co alloys  
Al-Ni-Co alloys

- **Applications:**

- They are used in magnetic detectors ,
- They are used in microphones.
- They are used in magnetic separators.
- They are used to make the permanent magnets.



# UNIT-III

# UNIT-III : PART-1: ELECTRO-MAGNETIC WAVES

## Maxwell's Equations

- \* Maxwell in 1862 formulated the basic law of electricity and magnetism in the form of '4' fundamental equations.
- \* These eq's are known as Maxwell's equations.
- \* The integral forms of these equations are given below.

$$\oint E \cdot ds = \frac{q}{\epsilon_0}$$

$$\oint B \cdot ds = 0$$

$$\oint E \cdot dl = -\frac{d\phi_B}{dt}$$

$$\oint B \cdot dl = \mu_0 \left( j + \epsilon_0 \frac{\partial E}{\partial t} \right)$$

- \* Maxwell's eq's can also be stated in the differential forms as follows:

$$\text{div } E = \frac{\rho}{\epsilon_0}$$

$$\text{div } B = 0$$

$$\text{curl } E = -\frac{\partial B}{\partial t}$$

$$\text{curl } B = \mu_0 \left( j + \epsilon_0 \frac{\partial E}{\partial t} \right)$$

### Derivations:

1.  $\oint E \cdot ds = \frac{q}{\epsilon_0}$  ( $\because$  Gauss' law for electricity)

- \* If  $\rho$  be charge density and  $dv$ , the small volume considered, then
- $$q = \int \rho dv$$

$$\oint E \cdot ds = \frac{1}{\epsilon_0} \cdot \int e \cdot dv$$

$$\text{or} \\ \oint \epsilon_0 \cdot E \cdot ds = \int e \cdot dv$$

$$\oint D \cdot ds = \int e \cdot dv \quad (\because \epsilon_0 E = D)$$

i.e., according to divergence theorem,

$$\oint A \cdot ds = \int_V (\vec{\nabla} \cdot A) dv$$

Hence,

$$\oint D \cdot ds = \int_V (\vec{\nabla} \cdot D) dv$$

so,

$$\int_V \vec{\nabla} \cdot D \cdot dv = \int_V e \cdot dv$$

$$\vec{\nabla} \cdot D = e \quad \text{or} \quad \vec{\nabla} \cdot E = \frac{\rho}{\epsilon_0}$$

$$\boxed{\text{div } E = \frac{\rho}{\epsilon_0}} \quad \text{--- (1)}$$

(or)

$$\frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} + \frac{\partial E_z}{\partial z} = \frac{\rho}{\epsilon_0}$$

2)  $\oint B \cdot ds = 0$  ( $\because$  Gauss law for magnetism)

\* Transforming the surface integral into volume integral,

we get,

$$\oint_S B \cdot ds = \int_V (\vec{\nabla} \cdot B) dv$$

$$\int_V (\vec{\nabla} \cdot B) \cdot dv = 0$$

As the volume is arbitrary, the integral must be 'zero'

$$\boxed{\vec{\nabla} \cdot B = 0}$$

(or)

$$\frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} + \frac{\partial B_z}{\partial z} = 0$$

$$3) \quad \oint \mathbf{E} \cdot d\mathbf{l} = -\frac{\partial \phi_B}{\partial t}$$

$$= -\frac{\partial}{\partial t} \int \mathbf{B} \cdot d\mathbf{s} = -\int \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{s}$$

Applying Stokes theorem

$$\oint \mathbf{E} \cdot d\mathbf{l} = \int (\nabla \times \mathbf{E}) \cdot d\mathbf{s}$$

$$\int (\nabla \times \mathbf{E}) \cdot d\mathbf{s} = -\int \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{s}$$

$$\boxed{\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}} \quad \text{--- (3)}$$

(or)

$$\text{curl } \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$4) \quad \oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 \cdot i \quad (\text{Ampere's law})$$

using Stokes theorem,

$$\oint \mathbf{B} \cdot d\mathbf{l} = \int (\nabla \times \mathbf{B}) \cdot d\mathbf{s}$$

$$\int (\nabla \times \mathbf{B}) \cdot d\mathbf{s} = \mu_0 \cdot \int \mathbf{j} \cdot d\mathbf{s}$$

$$\nabla \times \mathbf{B} = \mu_0 \cdot \mathbf{j}$$

(or)

$$\boxed{\nabla \times \mathbf{B} = \mu_0 \left( \mathbf{j} + \epsilon_0 \cdot \frac{\partial \mathbf{E}}{\partial t} \right)}$$

replacing  $\mathbf{j}$  by  $\left( \mathbf{j} + \frac{\partial \mathbf{E}}{\partial t} \right)$ .



## Electromagnetic wave propagation (Non-Conducting medium) :

\* Let us apply Maxwell's eq's to a homogeneous, isotropic dielectric medium. (including free space whose permittivity is  $\epsilon = \epsilon_0$ ). As the dielectric medium is one which offers infinite resistance to the current, and hence, its conductivity is zero, i.e.  $j = 0$ .

\* In homogeneous isotropic medium, there is no volume distribution of charge, thus, the charge density ' $\rho$ ' is zero. Hence,

$$j = 0, \quad \rho = 0, \quad D = k\epsilon_0, \quad E = \epsilon E$$

$$\& \quad B = \mu_0 \mu_r \cdot H, \quad H = \mu H$$

Hence, Maxwell's eq's for a dielectric (non-conducting medium)

become,

$$\vec{\nabla} \cdot E = 0 \quad \text{--- (1)}$$

$$\vec{\nabla} \cdot B = 0 \quad \text{--- (2)}$$

$$\vec{\nabla} \times E = -\frac{\partial B}{\partial t} \quad \text{--- (3)}$$

$$\vec{\nabla} \times B = \mu\epsilon \cdot \frac{\partial E}{\partial t} \quad \text{--- (4)}$$

\* we can obtain the eq of propagation of a wave in dielectric medium by eliminating  $E$  from eq (3) & (4).

Taking curl of eq (4), we get,

$$\begin{aligned} \vec{\nabla} \times \vec{\nabla} \times B &= \vec{\nabla} \times \mu\epsilon \cdot \frac{\partial E}{\partial t} = \mu\epsilon \left( \vec{\nabla} \times \frac{\partial E}{\partial t} \right) \\ &= \mu\epsilon \cdot \frac{\partial}{\partial t} (\vec{\nabla} \times E) \end{aligned}$$

( $\because \mu$  &  $\epsilon$  remain const throughout the medium).

$$= \mu \epsilon \cdot \frac{\partial}{\partial t} \left( -\frac{\partial B}{\partial t} \right) \quad \left( \because \vec{\nabla} \times E = -\frac{\partial B}{\partial t} \right)$$

from eq (3)

$$= -\mu \epsilon \cdot \frac{\partial^2 B}{\partial t^2}$$

Thus,  $\vec{\nabla} \times \vec{\nabla} \times B = -\mu \cdot \epsilon \cdot \frac{\partial^2 B}{\partial t^2}$  — (5)

we know that

$$\vec{\nabla} \times \vec{\nabla} \times B = \vec{\nabla} (\vec{\nabla} \cdot B) - \nabla^2 B = \vec{\nabla} \cdot 0 - \nabla^2 B \quad (\text{from eq (2)})$$

$$\vec{\nabla} \times \vec{\nabla} \times B = -\nabla^2 B \quad \text{--- (6)}$$

Substituting eq (6) in eq (5) we get

$$-\nabla^2 B = -\mu \cdot \epsilon \cdot \frac{\partial^2 B}{\partial t^2}$$

$$\boxed{\nabla^2 B = \mu \cdot \epsilon \cdot \frac{\partial^2 B}{\partial t^2}} \quad \text{--- (7)}$$

\* from eq (3), we can show that

let us take the curl of eq (3), we have

$$\begin{aligned} \vec{\nabla} \times (\vec{\nabla} \times E) &= \vec{\nabla} \times \left( -\frac{\partial B}{\partial t} \right) = -\frac{\partial}{\partial t} (\vec{\nabla} \times B) \\ &= -\mu \epsilon \frac{\partial}{\partial t} \left( \frac{\partial E}{\partial t} \right) = -\mu \epsilon \frac{\partial^2 E}{\partial t^2} \quad (\text{from eq (4)}) \end{aligned}$$

So,  $\vec{\nabla} \times \vec{\nabla} \times E = -\mu \epsilon \cdot \frac{\partial^2 E}{\partial t^2}$  — (8)

we know that

$$\begin{aligned} \vec{\nabla} \times \vec{\nabla} \times E &= \vec{\nabla} (\vec{\nabla} \cdot E) - \nabla^2 E \\ &= 0 - \nabla^2 E \quad \text{--- (9)} \end{aligned}$$

from eq (8) & (9), we get

$$\boxed{\nabla^2 E = \mu \cdot \epsilon \cdot \left( \frac{\partial^2 E}{\partial t^2} \right)}$$

## Poynting theorem

"The amount of field energy passing through unit area of the surface perpendicular to the direction of propagation of energy is called as Poynting vector".

\* For EM, In a plane electromagnetic wave,  $E$  &  $B$  are  $\perp$  to each other & also to the direction of wave propagation.

$$P = \frac{1}{\mu_0} (E \times B) \quad (\text{or}) \quad (E \times H).$$

$P$  - Poynting vector

Derivation :

\* Consider an elementary volume in the form of a rectangular parallel-piped of sides  $dx$ ,  $dy$  &  $dz$  as shown in fig. 4

\* The volume of parallel-piped is  $dx \cdot dy \cdot dz$ .

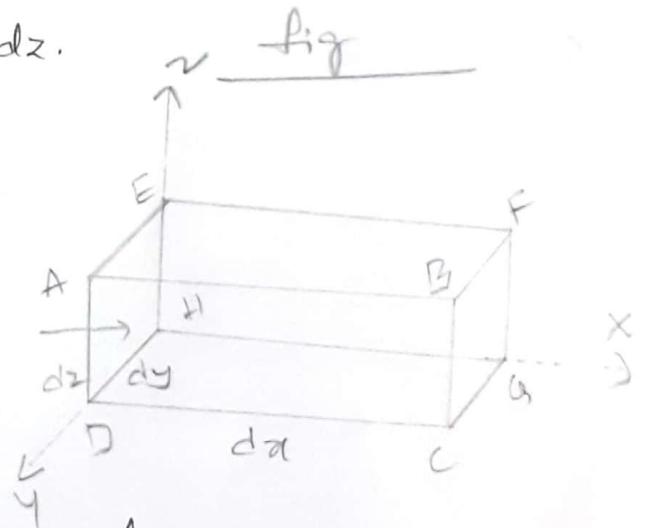
\* Suppose the electromagnetic energy is propagated along the  $X$ -axis. Now the area  $\perp$  to the direction of propagation of energy is  $dy \cdot dz$ .

\* Let the e.m energy in this volume is  $U$ .

Then the rate of change of energy is  $\frac{\partial U}{\partial t}$ .

$$\therefore \frac{\partial U}{\partial t} = - \oint_S P \cdot ds \quad \text{--- (1)}$$

'-ve' sign is used to show that energy is entering in the volume. So,  $\oint_S P \cdot ds = - \frac{\partial U}{\partial t}$ . --- (2)



Total energy  $U = u_E + u_B$

$\therefore U = \left( \frac{1}{2} \epsilon_0 \cdot E^2 + \frac{1}{2} \mu_0 H^2 \right)$

the rate of decrease of energy in vol  $dv$  is given by

$$-\frac{\partial}{\partial t} \left( \frac{1}{2} \epsilon_0 \cdot E^2 + \frac{1}{2} \mu_0 H^2 \right) dv$$

$\therefore$  Rate of decrease of energy for vol  $v$

$$\begin{aligned} -\frac{\partial U}{\partial t} &= -\frac{\partial}{\partial t} \int_V \left( \frac{1}{2} \epsilon_0 \cdot E^2 + \frac{1}{2} \mu_0 \cdot H^2 \right) \cdot dv \\ &= -\frac{\partial}{\partial t} \int_V \left( \frac{1}{2} \epsilon_0 \cdot E \cdot E + \frac{1}{2} \mu_0 \cdot H \cdot H \right) dv \\ &= -\int_V \left[ \epsilon_0 E \left( \frac{\partial E}{\partial t} \right) + \mu_0 H \left( \frac{\partial H}{\partial t} \right) \right] dv \quad \text{--- (3)} \end{aligned}$$

From maxwell's eq's

$$\vec{\nabla} \times H = \vec{j} + \frac{\partial D}{\partial t} = \frac{\partial D}{\partial t}$$

( $\because$  waves are propagating in non-conducting medium)

$$= \epsilon_0 \frac{\partial E}{\partial t}$$

$$\therefore \frac{\partial E}{\partial t} = \frac{1}{\epsilon_0} \cdot (\vec{\nabla} \times H) \quad \text{--- (4)}$$

Further,  $\vec{\nabla} \times E = -\frac{\partial B}{\partial t} = -\mu_0 \frac{\partial H}{\partial t}$

$$\frac{\partial H}{\partial t} = \frac{-\vec{\nabla} \times E}{\mu_0} \quad \text{--- (5)}$$

sub eq (5) & (4) & (3), we get

$$-\frac{\partial U}{\partial t} = \int_V - \left[ \epsilon_0 \cdot E \left( \frac{\vec{\nabla} \times H}{\epsilon_0} \right) + \mu_0 H \left( \frac{-\vec{\nabla} \times E}{\mu_0} \right) \right] dv \quad \text{--- (6)}$$

eq (6) can be written as

$$-\frac{\partial u}{\partial t} = \int_V [H \cdot (\nabla \times E) - E \cdot (\nabla \times H)] dV$$

$$= \int_V \nabla \cdot (E \times H) dV$$

$$[\because \nabla \cdot (A \times B) = B \cdot (\nabla \times A) - A \cdot (\nabla \times B)]$$

and ~~by~~ using Gauss theorem of divergence, the volume integral can be expressed in terms of surface integral,

$$\text{Thus, } = \oint_S (E \times H) \cdot n \, dS \quad \text{--- (7)}$$

$n$  - unit vector normal to the surface.

Comparing eq (3) with eq (2), we get

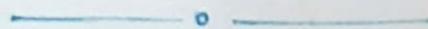
$$\oint_S P \cdot dS = \oint_S (E \times H) \cdot dS$$

$$(or) \quad \boxed{P = E \times H} \quad \text{--- (8)}$$

In magnitude  $P = EH$

\* This vector shows that energy flow takes place in a direction  $\perp$  to the plane containing  $E$  and  $H$  or  $B$ .

\* Hence  $E$  &  $H$  are the instantaneous values.



## Characteristics of Poynting vector:

\* The Poynting vector  $\vec{P}$  is  $\perp$  to both  $\vec{E}$  & magnetic field vector  $\vec{H}$ . So,  $\vec{P}$  is in the same direction as the direction of wave propagation.

\* The integral of  $\vec{P}$  over a closed surface, i.e.,

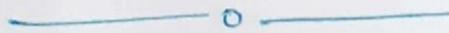
$$\oint \vec{P} \cdot d\vec{A} = \oint (\vec{E} \times \vec{H}) \cdot d\vec{A}$$

represents the rate at which e.m. energy crosses the closed surface.

\* The volume integral of  $\vec{\nabla} \cdot \vec{P}$ , i.e.,

$$\int \vec{\nabla} \cdot \vec{P} \cdot dV = \int \vec{\nabla} \cdot (\vec{E} \times \vec{H}) \cdot dV$$

represents the net energy flow in electromagnetic field.



## Divergence

(6)

\* The divergence of a vector field at any point is defined as the amount of flux per unit volume diverging from that point.

The divergence is a scalar.

\* Let  $A$  be a vector function differentiable at each point  $(x, y, z)$  in a region of space. Then

$$\begin{aligned}\nabla \cdot A &= \left( i \cdot \frac{\partial}{\partial x} + j \cdot \frac{\partial}{\partial y} + k \cdot \frac{\partial}{\partial z} \right) \cdot (i \cdot A_x + j \cdot A_y + k \cdot A_z) \\ &= \frac{\partial A_x}{\partial x} + \frac{\partial A_y}{\partial y} + \frac{\partial A_z}{\partial z}\end{aligned}$$

$$\therefore \text{div } A = \nabla \cdot A = \frac{\partial A_x}{\partial x} + \frac{\partial A_y}{\partial y} + \frac{\partial A_z}{\partial z}.$$

\* The divergence of current density,  $J$  gives the amount of charge flowing out per unit volume per second from a small element of closed surface around that point  $\nabla \cdot J = 0$ , shows that the medium is of free charges.

\* Imply  $\nabla \cdot B = 0$  in magnetism, shows that magnetic flux is a closed.

## Curl of a vector field :

\* So the curl of a vector field is defined as the maximum line integral of the vector per unit area. It is a vector quantity.

\* If  $A$  is a vector function differentiable at each point  $(x, y, z)$  in a region of a space, then the curl of  $A$  is

$$\text{Curl } A = \nabla \times A = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ A_x & A_y & A_z \end{vmatrix}$$

- \* when a current is passed through a conductor, then magnetic field is developed around it.
- \* At any nearby point, the curl of the magnetic field represents current per unit area passing through that point.
- \* So curl B is also known as magneto-motive force.
- \* The curl of an electric field results that rate of change of magnetic field in  $\perp$  direction.
- \* The curl of magnetic field results the flow of electricity.



## Gauss Theorem of divergence:

\* The theorem states that the surface integral of the normal component of vector  $A$  taken over a closed surface  $S$  is equal to the volume integral of the divergence of vector  $A$  over the volume  $V$  enclosed by the surface  $S$ , i.e.,

$$\iint_S A \cdot ds = \iiint_V \text{div} A \, dv = \iiint_V (\nabla \cdot A) \, dv.$$

\* This theorem provides a method for connecting volume integrals (Triple integrals) to surface integrals (double integrals).

Proof:

\* Consider a closed surface  $S$  of any arbitrary shape drawn in a vector field  $A$  of volume  $V$ .

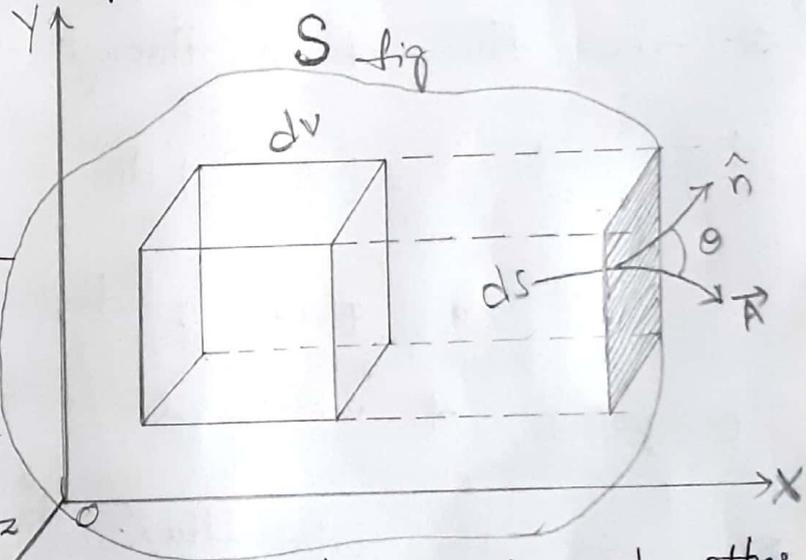
\* Now the whole volume may be assumed to be divided into a very large no. of cubical volume elements, adjoining to each other.

\* Consider a small cubical volume element, as shown in fig.

\* We know that  $\text{div} A$  represents the amount of flux divergence per unit volume.

\* Hence the flux diverging from the element of volume  $dv$  will be  $\text{div} A \cdot dv$ . So the total flux coming out from the entire volume is

$$\iiint_V \text{div} A \, dv \quad \text{--- (1)}$$



\* Now we consider a small element of area  $ds$  on the surface  $S$  as shown in fig.

\* Let  $\hat{n}$  represents the unit vector drawn normal to area  $ds$ .

It should be remembered that outward drawn normal on a surface is taken as +ve.

\* If the field vector  $A$  & outward normal  $\hat{n}$  are at an angle  $\theta$ , then the component of  $A$  along  $\hat{n}$  is

$$A \cos \theta = A \cdot \hat{n}$$

\* The flux of  $A$  through the surface element  $ds$  is given by

$$(A \cdot \hat{n}) ds = A \cdot ds$$

( $\therefore$  the flux is defined as the product of normal component of vector & surface area)

\* So the total flux through the <sup>entire</sup> surface  $S$  is given

by 
$$\iint_S A \cdot ds \quad \text{--- (2)}$$

\* This must be equal to the total flux divergence from the whole volume  $V$  enclosed by the surface  $S$ .

Hence from eq (1) & (2) we get

$$\iint_S A \cdot ds = \iiint_V \text{div} A \cdot dv \quad \text{--- (3)}$$

This is Gauss theorem of divergence.

This Gauss theorem may also be written as

$$\boxed{\iint_S (\mathbf{A} \cdot \hat{\mathbf{n}}) dS = \iiint_V (\nabla \cdot \mathbf{A}) dV} \quad \text{--- (4)}$$

### STROKE'S THEOREM

"This theorem states that the line integral of a vector field  $\mathbf{A}$  around a closed curve is equal to the surface integral of the curl of  $\mathbf{A}$  taken over the surface  $S$  surrounded by the closed curve, i.e.,"

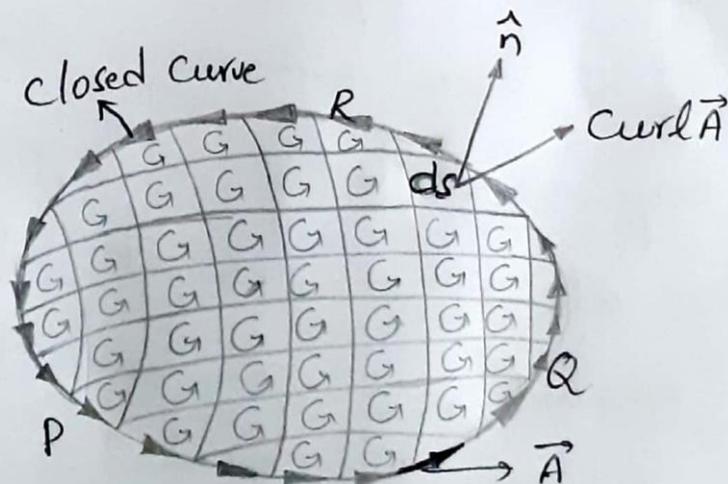
$$\oint_C \mathbf{A} \cdot d\mathbf{r} = \iint_S \text{curl } \mathbf{A} \cdot d\mathbf{S} = \iint_S (\nabla \times \mathbf{A}) \cdot d\mathbf{S}.$$

proof :

\* Consider a surface  $S$  enclosed in a vector field  $\mathbf{A}$ .

As shown in fig, the boundary of the surface  $S$  is closed curve PQR.

\* The line integral  $\mathbf{A}$  around the curve PQR traced counter-clockwise is



\* let the entire surface be divided into a large no. of square loops.

\* let the area enclosed by each infinitesimally small loop be  $ds$ .

\* Suppose  $\hat{n}$  be a unit positive outward normal upon  $ds$ .  
the vector area of the element is

$$\hat{n} \cdot ds = ds \quad \text{--- (1)}$$

\* we know that the curl of a vector field at any point is the maximum line integral of the vector computed per unit area along the boundary of infinitesimal area at the point.

\* So the line integral of  $A$  around the boundary of the area  $ds$  is

$$\text{curl } A \cdot ds \quad \text{--- (2)}$$

This is surface integral of  $A$ .

\* It is clear from fig that the line integrals along the common sides of the continuous elements mutually cancel because they are traversed in opposite directions.

\* Now the sides of the element which lie in the periphery of the surface (i.e. in the closed ~~surf.~~ curve) contribute to the line integral.

\* The sum of the line integrals on the boundary line of the curve is given by eq (2). This is also given by eq (1). Hence

$$\oint_C A \cdot da = \iint_S \text{curl } A \cdot ds = \iint_S (\nabla \times A) \cdot ds \quad \text{--- (3)}$$

This is Stokes' theorem.

\* It is obvious from eq (3) that Stokes theorem gives a method to convert a surface integral into a line integral and vice versa.

\* When  $\text{curl } A$  is zero, the line integral of  $A$  over the closed path is zero. and hence the field is conservative.



## Fiber optics

### Introduction

In 1870 John Tyndall demonstrated that light follows the curve of a stream of water pouring from a container; it was this simple principle that led to the study and development of application of the fiber optics. The transmission of information over fibers has much lower losses than compared to that of cables. The optical fibers are most commonly used in telecommunication, medicine, military, automotive and in the area of industry. In fibers, the information is transmitted in the form of light from one end of the fiber to the other end with min.losses.

### Advantages of optical fibers

1. Higher information carrying capacity.
2. Light in weight and small in size.
3. No possibility of internal noise and cross talk generation.
4. No hazards of short circuits as in case of metals.
5. Can be used safely in explosive environment.
6. Low cost of cable per unit length compared to copper or G.I cables.
7. No need of additional equipment to protect against grounding and voltage problems.
8. Nominal installation cost.
9. Using a pair of copper wires only 48 independent speech signals can be sent simultaneously whereas using an optical fiber 15000 independent speeches can be sent simultaneously.

### Basic principle of Optical fiber

The mechanism of light propagation along fibers can be understood using the principle of geometrical optics. The transmission of light in optical fiber is based on the phenomenon of total internal reflection.

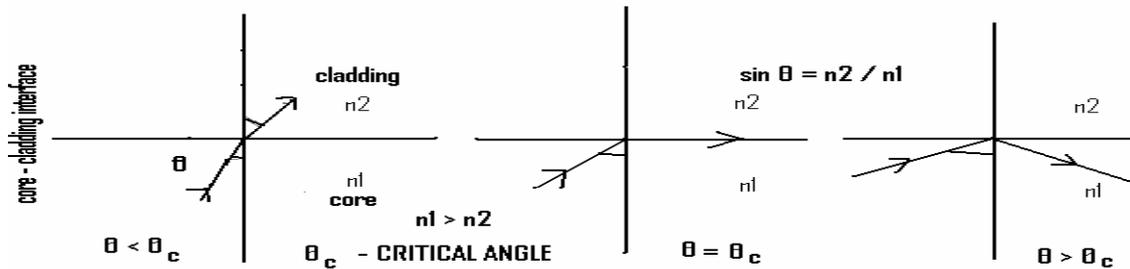
Let  $n_1$  and  $n_2$  be the refractive indices of core and cladding respectively such that  $n_1 > n_2$ . Let a light ray traveling from the medium of refractive index  $n_1$  to the refractive index  $n_2$  be incident with an angle of incidence “i” and the angle of refraction “r”. By Snell’s law

$$N_1 \sin i = n_2 \sin r \dots\dots\dots(1)$$

The refractive ray bends towards the normal as the ray travels from rarer medium to denser medium .On the other hand ,the refracted ray bends away from normal as it travel from denser medium to rarer medium. In the later case, there is a possibility to occur total internal reflection provided, the angle of incidence is greater than critical angle ( $\theta_c$  ).

This can be understood as follows.

1. When  $i < \theta_c$  then the ray refracted is into the second medium as shown in below fig1.
2. When  $i = \theta_c$  then the ray travels along the interface of two media as shown in fig2.
3. When  $i > \theta_c$  then the ray totally reflects back into the same medium as shown in fig3.



Suppose if  $i = \theta_c$  then  $r = 90^\circ$ , hence

$$n_1 \sin \theta_c = n_2 \sin 90^\circ$$

$$\sin \theta_c = n_2 / n_1 \text{ (since } \sin 90^\circ = 1\text{)}$$

$$\theta_c = \sin^{-1} \frac{n_2}{n_1} \text{ (2)}$$

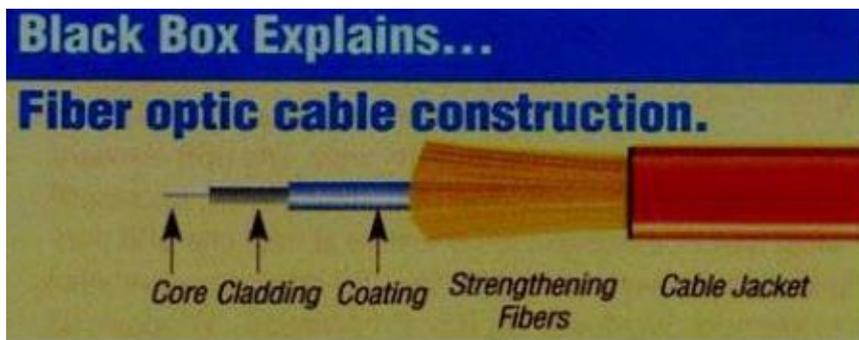
Thus any ray whose angle of incidence is greater than the critical angle ,total internal reflection occurs ,when a ray is traveling from a medium of high refractive index to low refractive index.

### Construction of optical fiber

The optical fiber mainly consists of the following parts.

- Core
  - Cladding
  - Silicon coating
  - Buffer jacket
  - Strength material
  - Outer jacket
- 
- A typical glass fiber consists of a central core of thickness  $50\mu\text{m}$  surrounded by cladding.
  - Cladding is made up of glass of slightly lower refractive index than core's refractive index, whose over all diameter is  $125\mu\text{m}$  to  $200\mu\text{m}$ .

- Of course both core and cladding are made of same glass and to put refractive index of cladding lower than the refractive index of core, some impurities like Boron, Phosphorous or Germanium are doped.
- Silicon coating is provided between buffer jacket and cladding in order to improve the quality of transmission of light.
- Buffer jacket over the optical fiber is made of plastic and it protects the fiber from moisture and abrasion.
- In order to provide necessary toughness and tensile strength, a layer of strength material is arranged surrounding the buffer jacket.
- Finally the fiber cable is covered by black polyurethane outer jacket. Because of this arrangement fiber cable will not be damaged during hard pulling, bending, stretching or rolling, though the fiber is of brittle glass.



### Acceptance angle and Numerical aperture of optical fiber

When the light beam is launched into a fiber, the entire light may not pass through the core and propagate. Only the rays which make the angle of incidence greater than critical angle at the core – cladding interface undergoes total internal reflection. The other rays are refracted to the cladding and are lost. Hence the angle we have to launch the beam at its end is essential to enable the entire light to pass through the core. This maximum angle of launch is called acceptance angle.

Consider an optical fiber of cross sectional view as shown in figure  $n_0$ ,  $n_1$  and  $n_2$  are refractive indices of air, core and cladding respectively such that  $n_1 > n_2 > n_0$ . Let light ray is incidenting on interface of air and core medium with an angle of incidence  $\alpha$ . This particular ray enters the core at the axis point A and proceeds after refraction at an angle  $\alpha_r$  from the axis. It then undergoes total internal reflection at B on core at an internal incidence angle  $\theta$ .

To find  $\alpha$  at A:-

In triangle ABC,  $\alpha_r = 90 - \theta$  ..... (1)

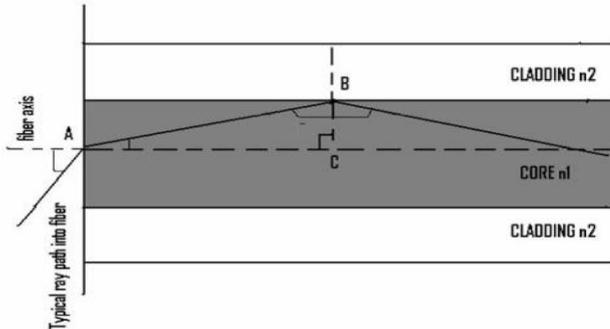
From Snell's law,

$$n_0 \sin \alpha = n_1 \sin \alpha_r \dots\dots\dots (2)$$

$$\sin \alpha = (n_1/n_0) \sin \alpha_r \dots\dots\dots (3)$$

From equations 1, 3

$$\sin \alpha = n_1/n_0 \sin(90- \theta) \Rightarrow \sin \alpha = n_1/n_0 \cos \theta \dots\dots\dots (4)$$



If  $\theta < \theta_c$ , the ray will be lost by refraction. Therefore limiting value for the beam to be inside the core, by total internal reflection is  $\theta_c$ . Let  $\alpha(\max)$  be the maximum possible angle of incident at the fiber end face at A for which  $\theta = \theta_c$ . If for a ray  $\alpha$  exceeds  $\alpha(\max)$ , then  $\theta < \theta_c$  and hence at B the ray will be refracted.

Hence equation 4 can be written as

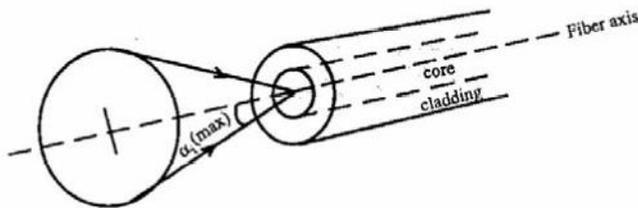
$$\sin \alpha(\max) = n_1/n_0 \cos \theta_c \dots\dots\dots (5)$$

We know that  $\cos \theta_c = \sqrt{1 - \sin^2 \theta_c} = \sqrt{1 - n_2^2/n_1^2}$   
 $= \sqrt{(n_1^2 - n_2^2)/n_1^2} \dots\dots\dots (6)$

Therefore

$$\sin \alpha(\max) = \sqrt{(n_1^2 - n_2^2)/n_0^2}$$

$$\alpha(\max) = \sin^{-1} \sqrt{(n_1^2 - n_2^2)/n_0^2}$$



Acceptance cone obtained by rotating the acceptance angle about the fiber axis

This maximum angle is called acceptance angle or acceptance cone angle. Rotating the acceptance angle about the fiber axis gives the acceptance cone of the fiber. Light launched at the fiber end within

this acceptance cone alone will be accepted and propagated to the other end of the fiber by total internal reflection. Larger acceptance angles make launching easier.

**Numerical aperture**

Light collecting capacity of the fiber is expressed in terms of acceptance angle using numerical aperture. Sine of the maximum acceptance angle is called the numerical aperture of the fiber.

$$\text{Numerical aperture} = \text{NA} = \sin \alpha (\text{max}) = \sqrt{(n_1^2 - n_2^2)/n_0} \dots \dots \dots (7)$$

$$\text{Let } \Delta = (n_1^2 - n_2^2)/2n_1^2 \dots \dots \dots (8)$$

For most fiber  $n_1 \approx n_2$

$$\text{Hence } \Delta = (n_1 + n_2)(n_1 - n_2)/2n_1^2 = 2n_1(n_1 - n_2)/2n_1^2$$

$$\Delta = (n_1 - n_2)/n_1 \text{ (fractional difference in refractive indices) } \dots \dots \dots (9)$$

$$\text{From equation (8) } n_1^2 - n_2^2 = \Delta 2n_1^2$$

Taking under root on both sides

$$\text{Hence } \sqrt{(n_1^2 - n_2^2)} = \sqrt{2} \Delta n_1$$

Substituting this in equation (7) we get

$$\text{NA} \approx \sqrt{2} \Delta n_1/n_0 \dots \dots \dots (10)$$

For air  $n_0 = 1$ , then the above equation can be changed as

$$\text{NA} \approx \sqrt{2} \Delta n_1$$

Numerical aperture of the fiber is dependent only on refractive indices of the core and cladding materials and is not a function of fiber dimensions.

**Types or classification of optical fibers**

Optical fibers are classified as follows:

Depending upon the refractive index profile of the core, optical fibers are classified into two categories

- 1) Step index
- 2) Graded index

Depending upon the number of modes of propagation, optical fibers are classified into two categories, they are

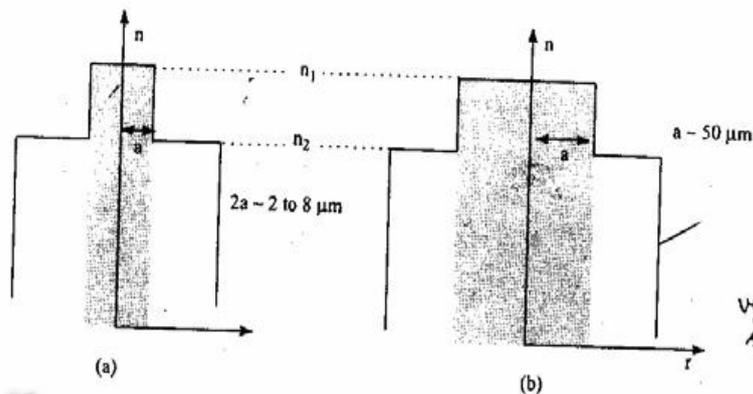
- 1) Single mode
- 2) Multi mode

Based on the nature of the material used, optical fibers are classified into four categories.

- 1) Glass fiber
- 2) Plastic fiber
- 3) Glass Core with plastic cladding
- 4) PCS Fibers(Polymer-Clad Silica fiber)\_

### Step index fibers

In step index fibers the refractive index of the core is uniform throughout the medium and undergoes an abrupt change at the interface of core and cladding. The diameter of the core is about 50-200 $\mu\text{m}$  and in case of multi mode fiber. And 10 $\mu\text{m}$  in the case of single mode fiber. The transmitted optical signals travel through core medium in the form of meridional rays, which will cross the fiber axis during every reflection at the core-cladding interface. The shape of the propagation appears in a zig-zac manner.



Refractive index profile for (a) monomode and (b) multimode step index fiber

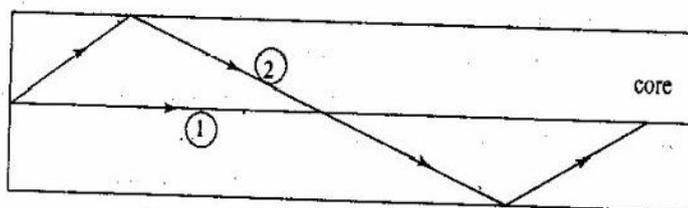
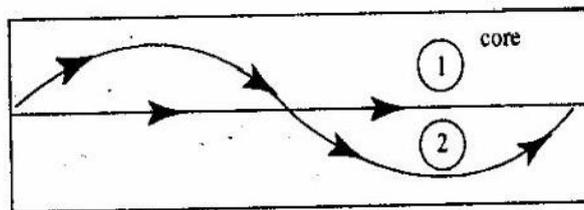
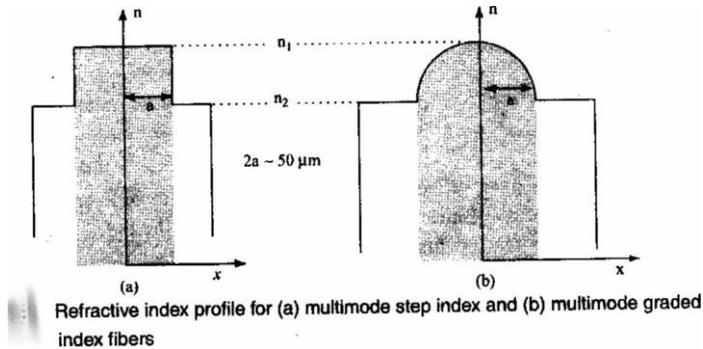


Fig. Signal transmission in step index fiber

### Graded index fiber

In these fibers the refractive index of the core varies radially. As the radius increases in the core medium the refractive index decreases. The diameter of the core is about 50 $\mu\text{m}$ .The transmitted optical

signals travel through core medium in the form of helical rays, which will not cross the fiber axis at any time.



Propagation of different model rays inside graded index fiber

### Attenuation and losses in fibres

When the light signal propagates in the optical fibre losses arise due to different factors and these losses are referred to as attenuation in optical fibre. The various factors causing attenuation in optical fibre are:

1. Material or impurity losses
2. Scattering losses
3. Absorption losses
4. Bending losses
5. Radiation losses
6. Inherent defect losses
7. Inverse square law losses
8. Transmission losses
9. Core and cladding losses

Losses are expressed in decibels per kilometer (dB/km). The attenuation loss is given by

$$P_{\text{out}} = P_{\text{in}} 10^{-\alpha L/10} \rightarrow (1)$$

where  $P_{out}$  = power at a distance L from the input

$P_{in}$  = amount of power coupled in to the fibre

$\alpha$  = fibre attenuation in dB/km and

L = length of the optical fibre

Therefore, attenuation in the fibre is defined as the ratio of the optical power output  $P_{out}$  obtained from a fibre of length 'L' to the optical power  $P_{in}$  fed to the input of the fibre

$\therefore$  from eqn(1), we have

$$\alpha = \frac{10}{L} \log\left(\frac{P_{in}}{P_{out}}\right) \text{ dB/km}$$

### Material or impurity losses

The doped impurities present in the fabrication of an optical fibre in order to vary the refractive index causes losses in the light signal propagation through the fibre.

### Scattering losses

In glass fibre the glass contains many microscopic in homogeneities and material content. Due to this, a portion of light signal passing through the glass fibre gets scattered. This scattering losses vary inversely with the fourth power of the wavelength.

### Absorption losses

Absorption loss is caused by the nature of core material and varies inversely to the transparency of the material. For glass fibres, ion-resonance absorption, ultraviolet absorption and infrared absorption are the three separate mechanisms which contribute to total absorption losses.

### Bending losses

Whenever a fibre deviates from a straight line path, radiative losses occur. These losses are prominent for improperly installed single mode optical cable.

### Radiation induced losses

When the glass molecular matrix interacts with electrons, neutrons, X-rays and gamma rays, the structure of the glass molecules is altered and the fibre darkens. This introduces additional losses which increase with amount, type, dose and exposure time of radiation.

### Inherent defect losses

The inherent defect present in core and cladding cause losses of the propagating light signal through it. The surface defect in the core cause losses in the light signal. Grease, oil and other contaminates on the surface of the fibre also causes signal losses due to variation of refractive index.

### Inverse square law losses

In all light systems, there is the possibility of losses caused by divergence of the beam. The illuminance per unit area is inversely proportional to the square of the distance ( $1/r^2$ ).

### Transmission losses

These losses are caused by light which is caught in the cladding material of optical fibres. This light is either lost to the outside, or is trapped in the cladding layer and is thus not available for propagation in the core of the fibre.

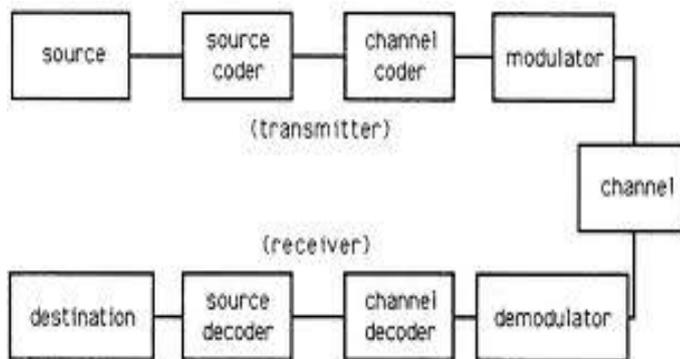
### Core and cladding losses

In a fibre core and cladding have different refractive indices, as they have different compositions. So the core and the cladding have different attenuation coefficients, causing the power losses to the fibre.

### Fibre optic communication system

A fundamental digital fibre optical communication system is shown in fig. Fibre optic communication system consists of three important components. They are

- 1) Optical transmitter
- 2) Fibre repeater
- 3) Optical receiver



### Optical transmitter

An optical transmitter converts an analogue or digital signal into optical form. It consists of an encoder, light source and modulator. The input analogue signal is converted into a digital signal by means of an encoder. The converted digital signal is fed to the source. The source can be a LED or a semiconductor laser diode. The optical carrier wave from the source is modulated based on intensity, amplitude or frequency with the help of a modulator. This optical signal is coupled to the optical fibre by means of couplers. The couplers launch the optical signal into the fibre without any distortion and loss. The optical signal through fibre is properly connected to a repeater with the help of a connector.

### Fibre repeater

The optical while travelling through very long optical fibers through long distances can suffer transmission losses and fibre losses like dispersion. As a result, we get a weak optical signal at the output end of the fibre. To minimise the losses, we use fibre repeaters at regular intervals between the fibres. The repeater consists of an amplifier and regenerator. The amplifier amplifies the weak optical signal, it is reconstructed to original optical signal with the help of regenerator and it is transmitted through the optical fibre. At the last stage, it is received by optical receiver.

### Optical receiver

The receiver unit consists of a photodetector, amplifier, demodulator and decoder. The photodetector consists of PIN photo diode or avalanche photo diode. This works on the principle of creation of an electron-hole pair at the p-n junction by successive collisions of the incident optical signal. The released electrons output a current which is in direct relationship with the incident optical signal. This electric current is then amplified and demodulated to obtain a digital signal. This signal is then decoded and the transmitted signal is outputted.

### **Advantages of optical fibres in communication**

- 1) Extremely wide band width
- 2) Smaller diameter, lighter weight cables
- 3) Lack of cross talk between parallel fibres
- 4) Immunity to inductive interference
- 5) Potential of delivering signals at low cost
- 6) Much safer than copper cables
- 7) Longer life span
- 8) High temperature resistance
- 9) Optical fibres are more reliable and easy to maintain than copper cables.

## **Applications of optical fibres**

### **Medicine**

- 1) Fibre scope in endoscopy is one of the widely used field optical technique to view the internal parts of the disease affected body.
- 2) This technique is widely used for diagnoses of interior of lungs, stomach and other human body parts.
- 3) Optical fibres are used in photodynamic therapy for cancer.
- 4) They are used in the treatment of lung disorders.
- 5) They are used in the treatment of bleeding ulcers.
- 6) They are used in the investigation of heart, respiratory system and pancreas.

### **Sensors**

Optical fibres were widely used in sensors for sending and measuring of acoustic fields, magnetic fields, currents, acceleration, strain, pressure, temperature, rotation, etc. Rotation sensing can be done with the help of fibre optic gyroscope.

A fibre optic sensor consists of a light source which generates light signals. These signals passes through the optical fibre placed in the sensing fields and then passes through the light detector. The variation in the light signal is caused by the sensing field and is detected by the detector as shown in fig. The optical fibre may be of single mode or multimode type.

### **Communication**

- 1) Optical fibres are extensively used in optical communication system.
- 2) Nearly 10,000 information carries signal can be transmitted simultaneously through the optical fibre.
- 3) Due to higher band widths optical fibre carries more information.
- 4) Without any crosstalk the information can be safely delivered.
- 5) During war time they are used for secret communication.
- 6) They are used for guiding weapons and submarine communication systems.

# UNIT-IV

## Unit-4 Semiconductors

### Semiconductors:

A Semiconductor is a substance whose conductivity or resistivity ( $10^{-4}$  to  $0.5 \text{ ohm -m}$ ) lies in between conductors and insulators.

Examples: Si, Ge, GaAs, AlAs and InP etc.

### Properties:

- They have crystalline structure.
- They are formed by covalent bonds.
- They have negative temperature of coefficient of resistance.
- At  $T=0\text{K}$ , they behaves as insulators.
- When the impurities (III group or V group elements) added to the pure semiconductor, then electrical conductivity increases.

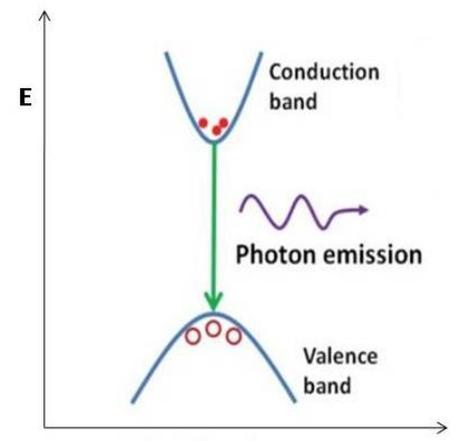
### Direct Band Gap And Indirect Band Semi Conductors:

Based on the type of energy emission the semiconductors can be of two groups.

1. Direct band gap semiconductors
2. Indirect band gap semiconductors

### Direct Band Gap Semi Conductors:

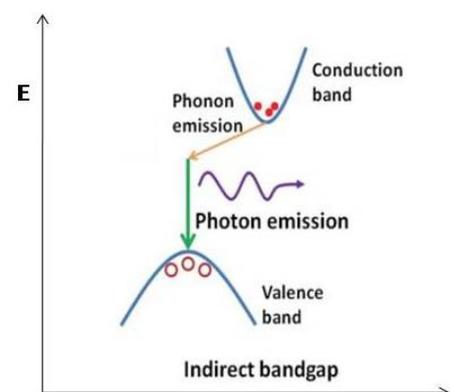
- The semiconductor, in which the minimum of the conduction band lies directly above the maximum of the valance band in the E-K space diagram ( as shown in fig), is known as direct band gap semiconductor.
- In a direct band gap semiconductor such as GaAs, AlAs and InP, when an excited electron falls back into the valance band, the electrons and holes recombine to produce light energy.  
*i.e.,  $\bar{e} + \text{hole} \longrightarrow hv \text{ (photon)}$*
- This process is known as radiative recombination and also called spontaneous emission.
- These direct band gap semiconductors are used to make LED's and lasers of different colours.



K

### Indirect Band Gap Semi Conductors:

- The semiconductor, in which the minimum of the conduction band does not lies directly above the maximum of the valance band in the E-K space diagram( as shown in fig), is known as indirect band gap semiconductor.
- In an indirect gap semiconductor such as Si, Ge and Gap, when an excited electron falls back into the valance band, the electrons and holes recombine to generate heat and is dissipated within the material.  
*i.e.,  $\bar{e} + \text{hole} \longrightarrow \text{phonon}$*
- This process is known as non-radiative recombination.

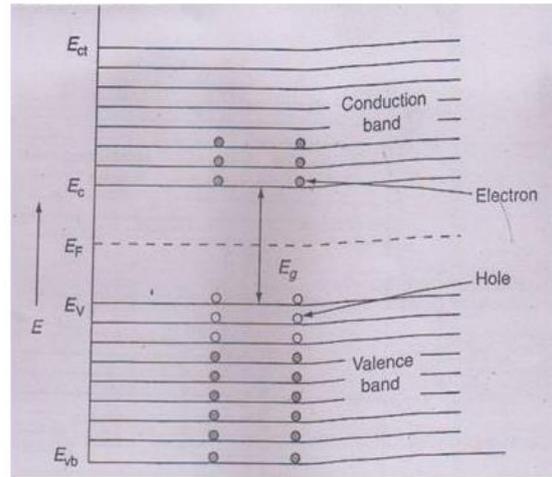
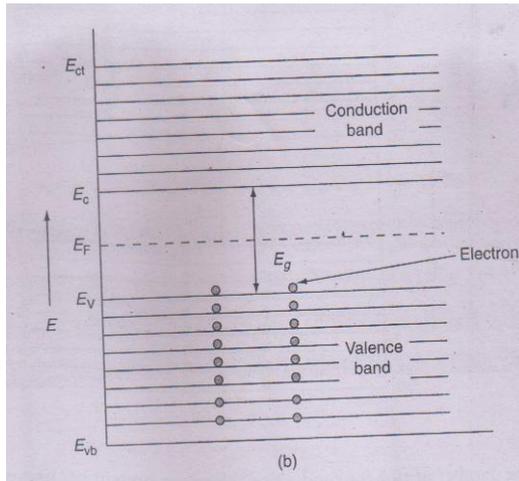


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### Intrinsic semiconductors and extrinsic semiconductors

Based on purity semiconductors are classified into





a) At  $T=0K$

b) At  $T > 0K$

- When electric field is applied across an intrinsic semiconductor, the current conduction takes place by two processes namely: by free electrons and holes.
- Therefore the total current inside the semiconductor is the sum of currents due to free electrons and holes

$$I = I_{\text{Electron}} + I_{\text{Hole}}$$

**Extrinsic Semi Conductor:**

The electrical conductivity of a pure semiconductor is very small. To increase the conductivity, impurities are added. The impurity added semiconductor is called “**Extrinsic Semi Conductor**”. (OR)

The conductivity of intrinsic semiconductor can be increased enormously by adding small amounts of impurity atoms [such as III or V group atoms]. This impure semiconductor is called “**Extrinsic Semi Conductor**”.

**Doping:**

The process of adding impurities to a semiconductor is called doping and the impurity added is called “**Dopant**”.

Depending upon the type of impurity added, Extrinsic Semiconductors are classified into two types.

1. N - Type Semi Conductor.
2. P - Type Semi Conductor

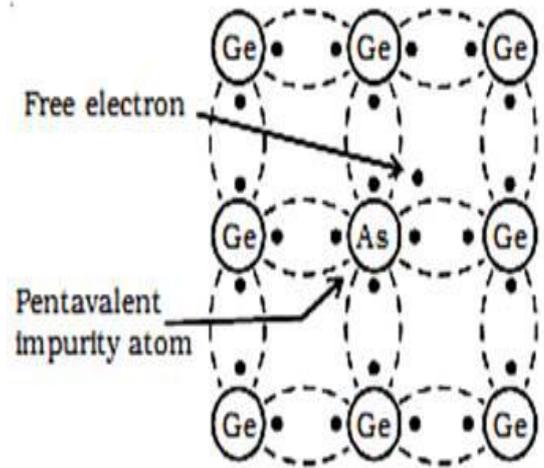
**N – Type Semi Conductor:**

When a small quantity of pentavalent impurity is added to a pure semiconductor, it is known as ‘n – type semiconductor’.

**Explanation:**

- To explain the formation of n-type semiconductor, consider a pure (semiconductor) Germanium Crystal.
- We know that germanium atom has four valence electrons, when a small amount of pentavalent impurities like arsenic (As) is added to a germanium crystal, a large number of free electrons available in the crystal.

- The reason is simple. Arsenic is pentavalent i.e., its atom has five valence electrons. The four of the five valence electrons of Arsenic will make covalent bonds with four germanium atoms. The fifth valence electron of arsenic atom finds no place in covalent bonds and is thus free as shown in fig.
- Therefore for each arsenic atom is added, one free electron will be available in the germanium crystal.
- Thus, a small amount of arsenic impurities (As) are added to a germanium crystal, a large number of free electrons available in the crystal.
- Pentavalent impurities are also known as donor impurities because they donate free electrons to semi conductor crystal.



### Energy Band Description:

- Fig (2) shows the energy band description of n-type semi conductor.
- The addition of donor impurity to an intrinsic semi conductor creates extra energy level (called donor energy level) just below the bottom of conduction band.
- **At Absolute Zero:** At absolute zero temperature the fifth electrons of arsenic atoms occupy the donor level (represented by dashed lines) as shown in fig.
- **At above Absolute Zero:** Even room temperature provides enough thermal energy to push the electrons sitting at donor energy level to conduction band. (The result is that at room temperature, there are a large number of free electrons in the conduction band as shown in fig) and also few of the covalent bonds in the semi conductor break due to the thermal energy applied.
- Due to the breaking of covalent bond, there will be a few holes formed in the valance band at this temperature. The result is that at room temperature, there are a large number of free electrons in the conduction band compared to the holes in valence band, i.e., Electrons are majority carriers and holes are minority carriers. So this material is called n-type semi conductor.

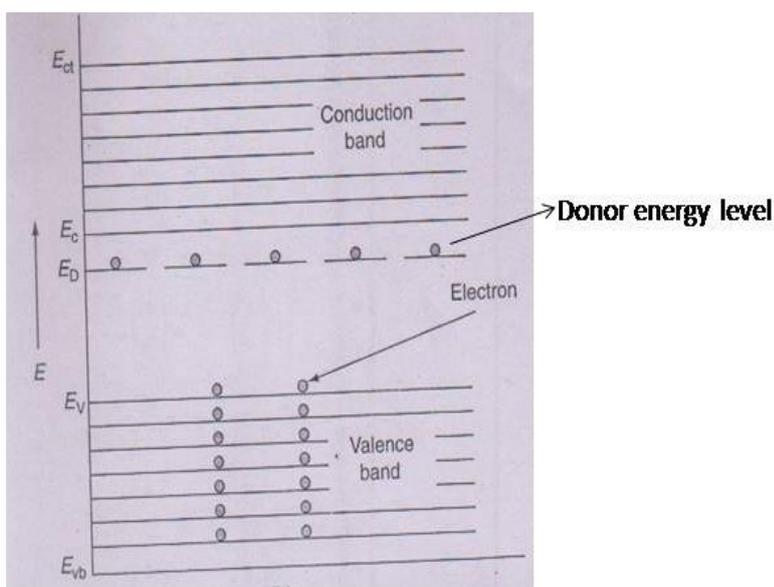
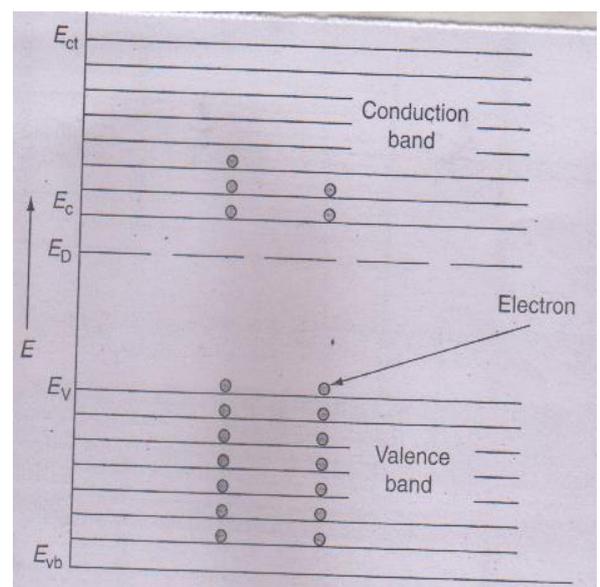


Fig: a) At T=0K



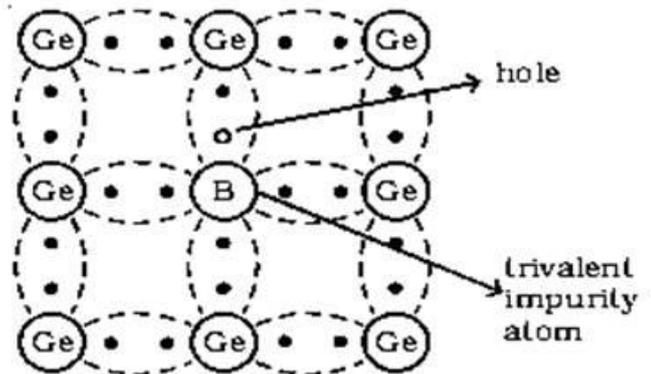
b) At T > 0K

## P-Type Semi Conductor:

When a small quantity of trivalent impurity (such as indium (In) Boron (B), aluminum (Al) etc. is added to a pure semi conductor, it is called P-type semi conductor.

### Explanation:

- To explain the formation of p-type semi conductor, consider a pure (semi conductor) Germanium Crystal.
- We know that germanium atom has four valence electrons, when a small amount of trivalent impurities like boron atoms (B) are added to a germanium crystal, a large number of holes available in the crystal.
- The reason is simple. Boron is trivalent i.e., its atom has three valence electrons. The three valence electrons of Boron atom will make three covalent bonds with surrounding Ge atoms.
- The fourth bond is incomplete because short of one electron. This missing electron is called a "hole".
- Therefore, for each boron atom is added, one hole will be available in the germanium crystal.



- Thus, a small amount of boron impurities (B) are added to a germanium crystal, a large number of free holes available in the crystal.
- Trivalent dopant impurities also called acceptors. Because they have need of extra electrons to complete their fourth covalent bonds formation with Ge atoms.
- **Energy Band Description:** Fig (2) shows the energy band description of p-type semi conductor. The addition of acceptor impurity to an intrinsic semi conductor creates extra energy level (called acceptor energy level) just above the top of the valence band [see fig].
- Since the energy difference between acceptor level and valence band energy level is very small so even at low temperature the valence band electrons gain sufficient thermal energy to occupy the acceptor energy level states as shown in fig.
- After receiving an electron the, Boron atom becomes a negative ion.
- But at room temperature provides enough thermal energy to push the electrons in the valence band to the acceptor energy level and also due to thermal agitation a few electrons jumps from V.B to C.B.
- The result is that at room temperature there are a large number of holes in the V.B compared to the electrons in the C.B. i.e., holes are majority carriers and electrons are minority carries. So, this material is called P-type semi conductors.

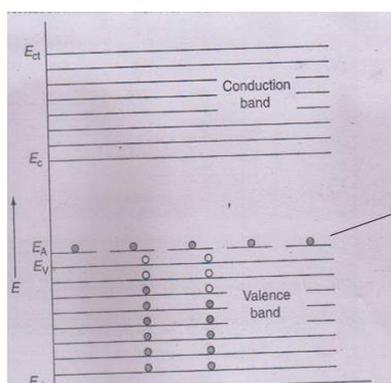
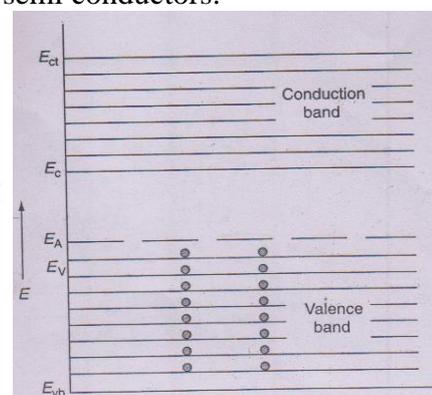


Fig: a) At  $T=0K$



b) At  $T > 0K$

## Electrical conduction in semiconductors

In the semiconductors electrical conduction arises due to two processes namely

1. Drift and
2. Diffusion

### Drift:

#### Definition:-

Under an applied electric field both the charge carriers i.e., electrons and holes acquire an average velocity called the drift velocity ( $V_d$ ) and this process is called drift.

The drift velocity  $V_d$  is small. It is directly proportional to the electrical field  $E$ .

$$\text{i.e., } V_d \propto E$$

$$V_d = \mu E \longrightarrow (1)$$

Where  $\mu$  is a constant and is called the mobility of charge carriers.

If  $\mu_n$  and  $\mu_p$  are the electron mobility and hole mobility respectively, then

$$V_n = \mu_n E \text{ and } \longrightarrow (2)$$

$$V_p = \mu_p E \longrightarrow (3)$$

1. We know that, Current  $I = ne AV_d$ .

But in a semi conductor, the total current is the sum of electrons current and holes current.

Let  $n$  be the electron concentration and  $p$  be the hole concentration.

Therefore  $I = I_n + I_p$

$$= neAV_n + pAV_p$$

$$= eA (nV_n + pV_p) \quad \text{[From equations (2) \&(3)]}$$

$$= eA(n \mu_n E + p \mu_p E)$$

$$= eA(n \mu_n + p \mu_p)E$$

2. Current density  $J = \frac{I}{A}$

$$J_n = \frac{neA\mu_n E}{A} \text{ and}$$

$$J_p = \frac{peA\mu_p E}{A}$$

Therefore, total current density  $J = J_n + J_p$

$$= \frac{eA(n\mu_n + P\mu_p)E}{A} = e(n\mu_n + P\mu_p)E$$

$$\text{Conductivity } \sigma = \frac{J}{E} = \frac{e(n\mu_n + P\mu_p)E}{E} = e(n\mu_n + P\mu_p)$$

**NOTE:-**

1. For an intrinsic semiconductor:  $n=p=n_i$

Where  $n_i$  is the carrier concentration of the intrinsic semiconductor.

$$I_{inc} = eA(n_i\mu_n + n_i\mu_p)E$$

$$= eAn_i(\mu_n + \mu_p)E$$

$$\therefore \text{Current density } J_{in} = \frac{I_{in}}{A} = \frac{eAn_i(\mu_n + \mu_p)E}{A} = en_i(\mu_n + \mu_p)E$$

$$\text{Conductivity } \sigma_{in} = \frac{J_{in}}{E} = \frac{en_i(\mu_n + \mu_p)E}{E} = en_i(\mu_n + \mu_p)$$

**FOR AN EXTRINSIC SEMICONDUCTOR:-**

a) **For n-type semiconductor :-** The hole current is neglected, as the holes are minority carriers and the electrons are the majority carriers.

$n \approx N_d$  is the donor electron concentration

[∴ Where  $N_a$  can be neglected]

$$I = eA V_n N_d$$

$$= eA\mu_n EN_d$$

$$J = \frac{I}{A} = e\mu_n EN_d$$

$$\sigma = \frac{J}{E} = e\mu_n EN_d$$

b) **For P-type semiconductor :-** The electron current is neglected and  $P=N_{ai}$ , where  $N_a$  is the acceptor hole concentration. [∴ When  $N_d$  can be neglected].

$$I = eA V_p N_a$$

$$= eA\mu_p E N_a$$

$$J = \frac{I}{A} = e\mu_p E N_a$$

$$\sigma = \frac{J}{E} = e\mu_p N_a$$

## **DIFFUSION :-**

Diffusion takes place due to existence of non-uniform concentration of charge carriers.

### **Definition:-**

Due to non –uniform carrier concentration in a semiconductor, the charge carrier's moves from a region of higher concentration to a region of higher concentration to a region of lower concentration. This process is known as diffusion of charge carriers.

→ According to Fick's law, the diffusion flux F is directly proportional to concentration gradient <i.e. carrier concentration per unit length >of the particles and is in the opposite direction.i.e;

$$F \propto \frac{-\partial(\Delta N)}{\partial X}$$
$$F = -D \frac{\partial(\Delta N)}{\partial X} \quad \longrightarrow \quad (1)$$

Where D is diffusion constant.

And  $\Delta N$  is the excess carrier concentration.

Let  $\Delta n$  and  $\Delta p$  be the excess concentration in a semiconductor material.

Then Fick's

$$F \propto \frac{-\partial(\Delta N)}{\partial X} \quad (\text{For electrons})$$
$$F = -D_n \frac{\partial(\Delta N)}{\partial X} \quad \longrightarrow \quad (2)$$

and

$$F \propto \frac{-\partial(\Delta P)}{\partial X} \quad (\text{For electrons})$$
$$F = -D_p \frac{\partial(\Delta P)}{\partial X} \quad \longrightarrow \quad (3)$$

→ But the current density due to diffusion depends on charge of particle and rate of diffusion.

∴ Current density (J) = Charge of particle × Rate of diffusion  $\longrightarrow$  (4)

→ The diffusion flux density due to electron is given by

$$J_{n(\text{Diff})} = -e \left[ -D_n \frac{\partial(\Delta N)}{\partial X} \right] \quad \therefore \text{from(4)}$$

$$J_{n(\text{Diff})} = e D_n \frac{\partial(\Delta N)}{\partial X} \quad \longrightarrow \quad (5)$$

The diffusion flux density due to hole is given by

$$J_{p(\text{Diff})} = + e \left[ D_p \frac{\partial(\Delta P)}{\partial X} \right] \quad \longrightarrow \quad (6)$$

Where +e and –e are charge of the hole and electron respectively.

∴ The total current density due to diffusion is given by

$$J_{\text{TOTAL,(DIFF)}} = J_{n(\text{diff})} + J_{p(\text{diff})}$$
$$J_{\text{TOTAL,(DIFF)}} = e D_n \frac{\partial(\Delta N)}{\partial X} - e D_p \frac{\partial(\Delta P)}{\partial X} \quad \longrightarrow \quad (7)$$

**NOTE:-** The total current density due to excess electrons is the sum of the current densities due to drift and diffusion of electrons.

$$J_n = J_{n(\text{drift})} + J_{n(\text{diff})}$$
$$= \Delta n \mu_n E + e D_n \frac{\partial(\Delta N)}{\partial X} \quad \longrightarrow \quad (8)$$

Similarly,

The total current density due to excess holes is the sum of the holes densities due to drift and diffusion of holes.

$$J_p = \Delta p e \mu_p E - e D_p \frac{\partial(\Delta P)}{\partial X} \quad \longrightarrow \quad (9)$$

### EINSTEIN'S RELATION:-

Einstein showed the direct relation between the mobility ( $\mu$ ) and diffusion coefficient (D) of a semiconductor. This relation is called Einstein relation.

At any disturbance in equilibrium, the drift and diffusion current densities due to carrier concentration are equal.

$$\begin{aligned} \text{i.e.;} \quad J_{n(\text{drift})} &= J_{n(\text{diff})} \\ (\Delta n) e E \mu_n &= D_n e \frac{\partial(\Delta n)}{\partial X} \quad \longrightarrow \quad (1) \end{aligned}$$

The force on excess electrons ( $\Delta n$ ) to restore equilibrium is given by the product of  $\Delta n$  and electric forces  $eE$  on each electron. Thus,

$$F = (\Delta n) e E \quad \longrightarrow \quad (2)$$

Equation (1) can be written as

$$\begin{aligned} F \cdot \mu_n &= D_n e \frac{\partial(\Delta n)}{\partial X} \\ F &= \frac{D_n}{\mu_n} e \frac{\partial(\Delta n)}{\partial X} \quad \longrightarrow \quad (3) \end{aligned}$$

From the kinetic theory of gases, the force on gas molecules (charge carriers) is given by

$$F = K_B T \frac{\partial(\Delta n)}{\partial X} \quad \longrightarrow \quad (4)$$

Comparing (3) and (4), we get

$$\begin{aligned} K_B T \frac{\partial(\Delta n)}{\partial X} &= \frac{D_n}{\mu_n} e \frac{\partial(\Delta n)}{\partial X} \\ K_B T &= \frac{D_n}{\mu_n} e \\ D_n &= \frac{\mu_n K_B T}{e} \\ \frac{D_n}{\mu_n} &= \frac{K_B T}{e} \quad \longrightarrow \quad (5) \end{aligned}$$

Similarly for holes,

$$\frac{D_p}{\mu_p} = \frac{K_B T}{e} \quad \longrightarrow \quad (6)$$

From equations (5) and (6)

$$\begin{aligned} \frac{D_n}{\mu_n} &= \frac{D_p}{\mu_p} \\ \frac{D_n}{D_p} &= \frac{\mu_n}{\mu_p} \end{aligned}$$

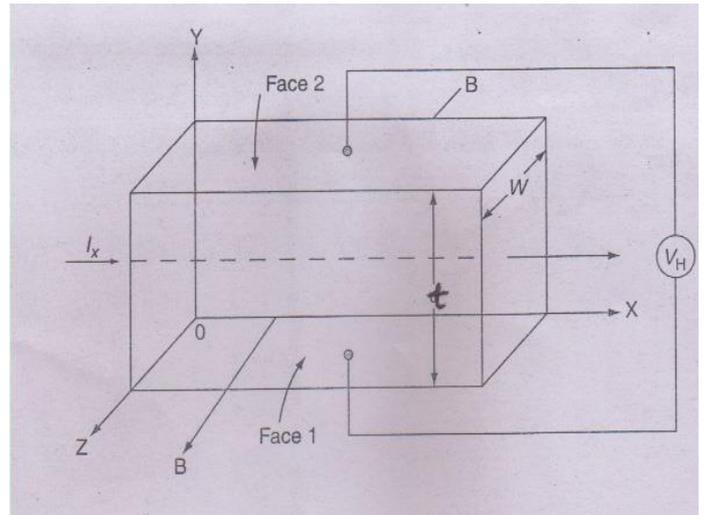
The above relation is known as Einstein's relation.

## Hall Effect:

When a current carrying semiconductor is placed in the magnetic field, then a potential difference (voltage) or electric field is developed in the material perpendicular to both the current and the applied magnetic field. This effect is known as Hall Effect and the developed potential difference (voltage) is known as Hall voltage.

## Explanation:

- Consider a semiconductor slab of thickness 't' and width 'w' in which current (I) is flowing along X-direction and magnetic field is applied along Z-direction as shown in fig.
- The charge carriers inside the semiconductor experience a force due to the applied magnetic field called Lorentz force.
- As a result, electrons move (drift) towards downward direction with velocity 'V<sub>d</sub>' and accumulate at bottom surface (face 1) and the corresponding positive charge on upper surface (face 2) of the material as shown in fig.
- Thus a potential difference and electric field developed across the surface. This developed electric field along Y-direction exerts a force (F<sub>e</sub> = eE<sub>H</sub>) on the electrons to prevent further accumulation at the bottom surface.
- Therefore, the force due to potential difference F<sub>e</sub> = eE<sub>H</sub>  
the force due to magnetic field F<sub>L</sub> = BeV<sub>d</sub>



At steady state

$$F_e = F_L$$

$$eE_H = Bev_d$$

$$E_H = Bv_d \longrightarrow (1)$$

## For n-type:

If 'n' is the electrons carrier concentration in the semiconductor, then current density

$$J = -nev_d$$

$$v_d = \frac{J}{-ne} \longrightarrow (2)$$

Substituting eq (2) in eq(1)

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

$$\boxed{E_H = R_H BJ} \longrightarrow (3)$$

Where  $R_H = \frac{1}{-ne}$  is known as Hall coefficient.

**For p-type:**

If 'p' is the electrons carrier concentration in the semiconductor, then current density

$$J = peV_d$$
$$V_d = \frac{J}{pe} \longrightarrow (2)$$

Substituting eq (2) in eq(1)

$$E_H = \frac{BJ}{pe}$$

$E_H = R_H BJ$

 $\longrightarrow (3)$

Where  $R_H = \frac{1}{pe}$  is known as Hall coefficient

**Hall coefficient in terms of hall voltage:**

If the thickness of the sample is 't' and the developed voltage is  $V_H$ , then the Hall voltage

$$V_H = E_H.t \longrightarrow (4)$$

Substituting eq (3) in eq(4);

$$V_H = R_H BJ t \longrightarrow (5)$$

If 'w' is the width of the semiconductor,  
then area of the sample  $A = w.t$

But current density  $J = \frac{I}{A} = \frac{I}{wt} \longrightarrow (6)$

Substituting eq (8) in eq(7); we get

$$V_H = \frac{R_H IB}{w}$$
$$R_H = \frac{V_H w}{IB}$$

$R_H = \frac{V_H w}{IB}$

This is the relation between Hall coefficient and hall voltage.

- The electrical conductivity in a semiconductor is given by

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

$\mu = R_H \sigma$

**APPLICATIONS:**

- Knowing  $R_H$  and  $\sigma$ , the mobility of charge carriers can be measured. *i. e.*,  $\mu = R_H \sigma$
- It is used to find the carrier concentration

$n = - \frac{1}{eR_H} \quad \text{and} \quad p = \frac{1}{eR_H}$

- It is used to determine whether the material is p-type or n-type semiconductor.  
*i.e.*, if  $R_H$  is negative then the material is n-type.  
if  $R_H$  is positive then the material is p-type.

### P-n junction:

When a p-type semiconductor is suitably joined to n-type semiconductor, the contact surface is established between them, is called p-n junction.

### Formation of p-n junction:

- The formation of p-n junction as shown in fig
- Let us consider the formation of a junction when two separate semiconductors of p and n-types are brought together.
- We know that, in a p-type semiconductor holes are the majority carriers and electrons are the minority carriers and in a n-type semiconductor free electrons are the majority carriers and holes are minority carriers.
- When they are joined ,due to non-uniform carrier concentration ,free electrons diffuse from n-region to p-region and recombine with holes and holes diffuse from p-region to n-region and recombine with electrons.
- As result, a net negative charge is created on the p-side and a net positive charge is created on the n-side. These charges produce the potential difference, is called potential barrier and this region is called depletion region because it opposes the further flow of electrons from n-region to p-region.
- The potential barrier is the order of 0.1 to 0.3 volt.

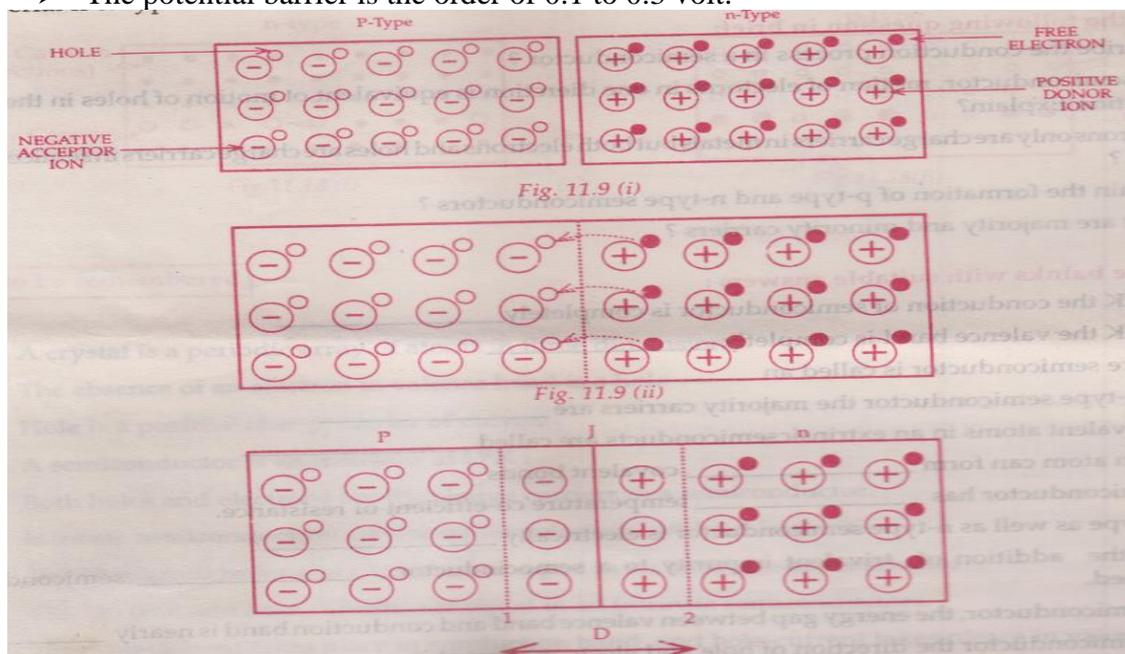
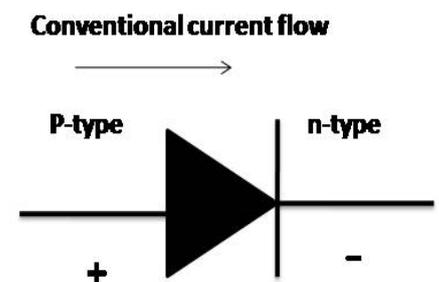


Fig: Formation of p-n junction

### P-n junction diode:

- A two electrode device is called diode.
- In the p-n junction, p-type semiconductor and n-type semiconductors behaves as electrodes.
- The symbol for the p-n junction diode is shown in fig.
- In fig, arrow of head indicates a p-type semiconductor and shows the direction of conventional current flow when the junction is forward biased, and the bar indicates a n-type semiconductor.



## Bias:

To apply an external voltage to the p-n junction is called bias.

Bias can be divided into two types

1. Forward bias
2. Reverse bias

### Forward bias:

- When a p-type semiconductor is connected to the positive terminal of the battery and n-type semiconductor is connected to the negative terminal of the battery, then it is known as forward bias.
- When the junction is forward biased
  - a) The width of depletion region is decreased
  - b) The potential barrier is reduced
  - c) The Junction offers a very low resistance.
  - d) Electrons flows from n-region to p-region through the junction and this gives rise to forward current
  - e) Current is in the order of mA

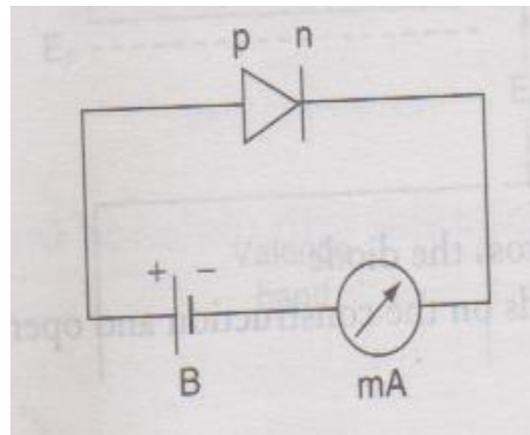
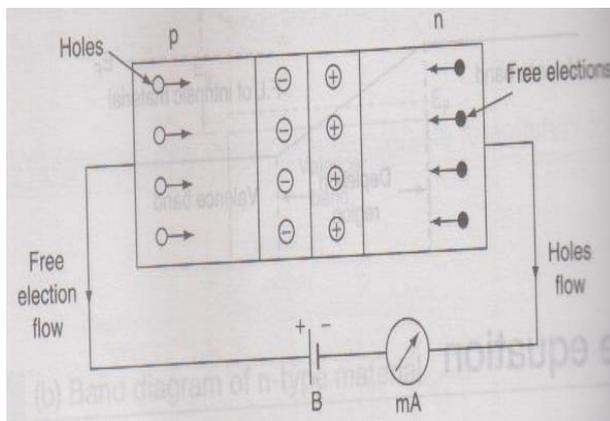


Fig: Forward bias p-n junction

### Reverse bias:

When a p-type semiconductor is connected to the negative terminal of the battery and n-type semiconductor is connected to the positive terminal of the battery, then it is known as reverse bias.

When the junction is reverse biased

- a) The width of depletion region is increased
- b) The potential barrier is increased
- c) The Junction offers a very high resistance.
- d) Current is in the order of  $\mu\text{A}$

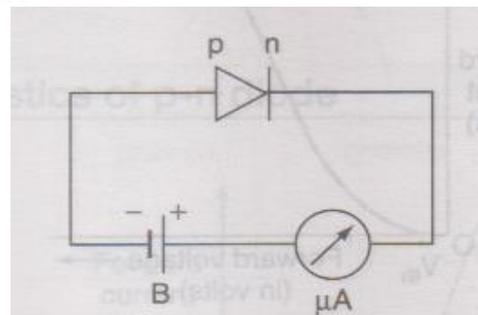
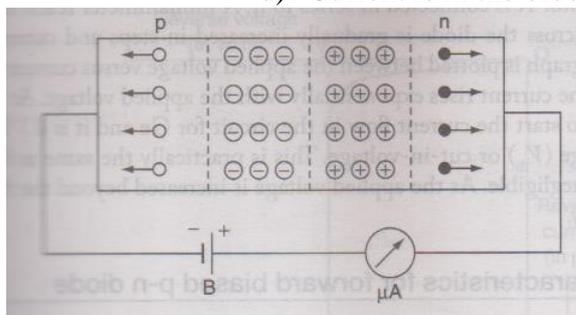


Fig: Reverse bias p-n junction

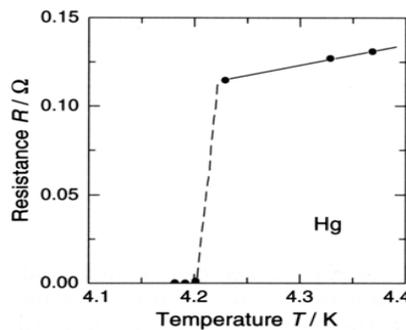
**UNIT-V**

# Unit-5-Superconductivity & Nano Materials

## Introduction:

**Super conductivity is the phenomenon in which the electrical resistance of certain materials becomes zero at very low temperatures.**

For example, the electrical resistance of pure mercury suddenly drops to zero, when it is cooled below 4.2 Kelvin and becomes a superconductor. This was first observed by the Dutch physicist, Heike Kammerlingh Onnes on April 8, 1911. Further, the theory of super conductivity was developed in 1957 by three American physicists-John Bardeen, Leon Cooper, and John Schrieffer, through their Theories of Superconductivity, known as the **BCS Theory**.



**Figure:** The resistance of mercury measured by Onnes.

## Super conductors:

A Super conductor is a material that loses all its resistance to flow of electric current, when it is cooled below a certain low temperature.

### **Examples:**

Material	Type
Tungsten	Metal
Zinc	Metal
Aluminum	Metal
Tin	Metal
Mercury	Metal
Lead	Metal
NbTi	Inter metallic compound
Nb <sub>3</sub> Sn	Inter metallic compound
Nb <sub>3</sub> Ge	Inter metallic compound
YBa <sub>2</sub> Cu <sub>3</sub> O <sub>7</sub>	Ceramic
TlBaCaCuO	Ceramic

## General properties of super conductor:

- Superconductivity is the physics of the Cooper Pairs. It occurs due to the movement of electron pairs called Cooper pairs through the lattice points. These Cooper pairs are formed due to the **electron –lattice –electron interaction**.
- Super conductivity is a low-temperature phenomenon.
- The electrical resistivity of a super conducting material is very low and is the order of  $10^{-5} \Omega\text{cm}$ .

- The temperature at which a normal conductor loses its resistivity and becomes a super conductor is known as transition temperature or critical temperature ( $T_C$ ). Different materials will have different critical temperatures.
- When impurities are added to superconducting elements, the super conducting property is not lost, but the  $T_c$  value is lowered.
- The critical temperature ( $T_c$ ) decreases with increasing isotopic mass  $M$ . This effect is known as isotope effect.

$$\text{i.e., } T_c \propto M^{-\frac{1}{2}}$$

- The magnetic field at which super conductor loses its super conductivity and becomes normal conductor is known as critical magnetic field  $H_c$ . Different materials will have different  $H_c$  values.
- Super conductors do not allow magnetic flux through them and behave as a diamagnetic. This property of expulsion of magnetic flux is known as meissner effect.
- Ferromagnetic materials like Fe, Co, Ni do not show superconductivity.
- The magnetic flux ( $\Phi$ ) lines passing through a super conducting ring due to persistent current is quantized in terms of integral multiples of  $\frac{h}{2e}$

$$\Phi = \frac{nh}{2e}$$

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

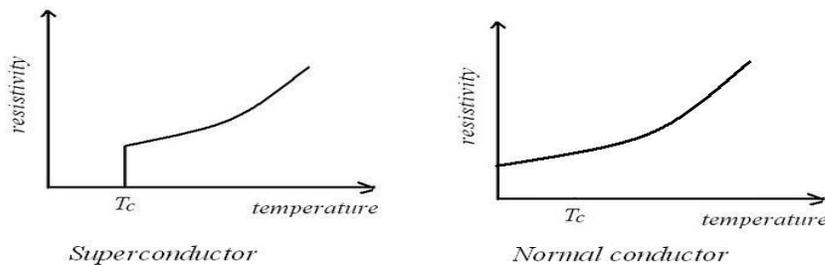
Where  $\frac{h}{2e}$  is known as fluxion (or) fluxiod. =  $2.07 \times 10^{-15}$

Weber's.

### Effect of temperature-Critical temperature:

In the year 1911, kammerligh Onnes observed that the electrical resistance of pure mercury suddenly drops to zero, when it is cooled below 4.2 Kelvin and becomes a superconductor.

The temperature at which a normal conductor loses its resistivity and becomes a super conductor is known as transition temperature or critical temperature ( $T_C$ ) as show in fig.



$T_c$  = critical temperature

<http://funk-funk.blogspot.com>

**Fig: The variation of electrical resistance with temperature**

Figure shows the variation of electrical resistivity with temperature. Below  $T_C$  the material is said to be in the superconducting state and above  $T_C$  the material is said to be in non-superconducting state (i.e., normal state). The value of this critical temperature varies from material to material.

Material	Type	T <sub>c</sub> (K)
Tungsten	Metal	0.01
Zinc	metal	0.88
Aluminum	metal	1.19
Tin	metal	3.72
Mercury	metal	4.15
Lead	metal	7.2
NbTi	Inter metallic compound	9.5
Nb <sub>3</sub> Sn	Inter metallic compound	21
Nb <sub>3</sub> Ge	Inter metallic compound	23.2
YBa <sub>2</sub> Cu <sub>3</sub> O <sub>7</sub>	ceramic	90
TlBaCaCuO	ceramic	125

### **High temperature superconductors:**

Super conductors are divided into two types based on their transition temperatures.

a) Low T<sub>C</sub> super conductors

b) High T<sub>C</sub> super conductors

If a transition temperature is low (below 30 K), then the superconductors are known as low temperature superconductors.

If a transition temperature is high (above 30 K), then the superconductors are known as high temperature superconductors.

The first high-T<sub>c</sub> superconductor was discovered in 1986 by [Georg Bednorz](#) and Muller, in ceramics. They found that the mixed metallic oxide of lanthanum-barium-copper (La<sub>1</sub>Ba<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub>) exhibited superconductivity at about 30 K.

Further it has been developing by many scientists and co-research scholars.

### **Some examples are:**

S.No	Material	T <sub>C</sub> K
1	Ba-pbBi-O <sub>3</sub>	38
2	YBa <sub>2</sub> Cu <sub>3</sub> O <sub>7</sub>	92
3	Bi <sub>2</sub> Sr <sub>2</sub> CaCu <sub>2</sub> O <sub>8</sub>	85
4	Bi <sub>2</sub> Sr <sub>2</sub> Ca <sub>2</sub> Cu <sub>3</sub> O <sub>6</sub>	110
5	Tl <sub>2</sub> Ba <sub>2</sub> CuO <sub>6</sub>	80
6	Tl <sub>2</sub> Ba <sub>2</sub> CaCu <sub>2</sub> O <sub>8</sub>	108
7	Tl <sub>2</sub> Ba <sub>2</sub> Ca <sub>2</sub> Cu <sub>3</sub> O <sub>10</sub>	125
8	TlBa <sub>2</sub> Ca <sub>3</sub> Cu <sub>4</sub> O <sub>11</sub>	122
9	HgBa <sub>2</sub> CuO <sub>4</sub>	94
10	HgBa <sub>2</sub> CaCu <sub>2</sub> O <sub>6</sub>	128
11	HgBa <sub>2</sub> Ca <sub>2</sub> Cu <sub>3</sub> O <sub>8</sub>	134

### **Properties:**

Some of the properties of high T<sub>C</sub> superconductors as follows:

1. They have high transition temperature.
2. They are brittle in nature.
3. They are highly anisotropic.
4. They are reactive, brittle and can't be easily formed or joined.
5. They are oxides of copper in combination with other elements.
6. The hall coefficient is positive indicating that the charge carriers are holes.
7. Their behavior can't be explained by BCS theory.

**Effect of magnetic field - Critical magnetic field:**

Kammerlingh Onnes observed in 1913 that superconductivity vanishes if a sufficiently strong magnetic field is increased.

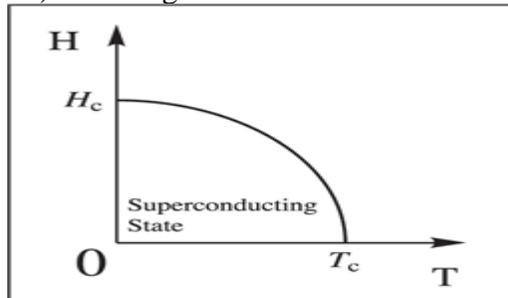
When a magnetic field is applied to a super conductor, then particular value of applied field and below its critical temperature, it loses super conductivity and becomes a normal conductor. This minimum magnetic field required to destroy the super conducting state is called the critical magnetic field  $H_C$ .

The critical magnetic field of a superconductor is a function of temperature. The variation of  $H_C$  with temperature is given by

$$H_C = H_0 \left[ 1 - \left( \frac{T}{T_C} \right)^2 \right]$$

Where  $H_C$  = critical magnetic field,  
 $H_0$  = critical magnetic field at  $T=0K$ , and  
 $T_C$  = critical temperature.

Figure shows the variation of critical magnetic field  $H_C$  as a function of temperature. The material is said to be in the superconducting state within the curve and is non super conducting (i.e., normal state) in the region the outside the curve.



**Figure:** Effects of temperature and magnetic field on the superconducting state.

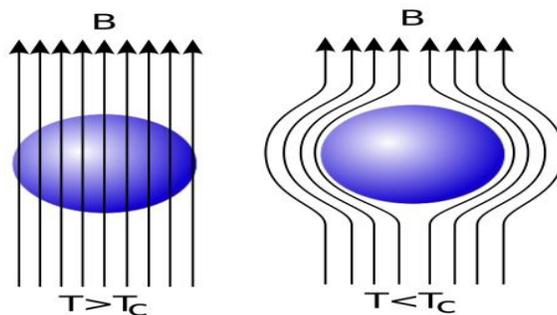
**Meissner effect:**

When the super conducting material is placed in magnetic field, under the condition when  $T \leq T_C$  and with  $H \leq H_C$  the flux lines are expelled from the material. Thus the material exhibits perfect diamagnetism. This phenomenon is called as Meissner effect.

**Explanation:**

Consider a normal conducting material at room temperature. When a magnetic field  $H$  is applied to it, then it allows the magnetic lines of force to pass through it. Thus we have a magnetic field  $B$  in a conductor as shown in fig (1).

Now, when the material is cooled below its critical temperature ( $T \leq T_C$ ) and with  $H \leq H_C$ , then the magnetic lines of forces are expelled or ejected out from the material as shown in fig(2).



**Fig (1): Normal state ( $B \neq 0$  at  $T > T_C$ ).**      **Fig (2): Superconducting state. ( $B=0$  at  $T < T_C$ )**

**Proof:**

We know that, the total magnetic flux density in a normal conductor is given by

$$B = \mu_0 (M + H) \dots\dots\dots (1)$$

Where  $\mu_0$  is the permeability of free space =  $4\pi \times 10^{-7}$  H/m

M is the intensity of magnetization

and, H is the applied magnetic field strength.

But, for superconductor  $B = 0$

Therefore, equation (1) can be written as

$$0 = \mu_0 (M + H)$$

$$[\because \mu_0 \neq 0]$$

$$M + H = 0$$

$$\text{or } M = -H$$

$$\text{or } \frac{M}{H} = -1$$

Hence,  $\chi_m = \frac{M}{H} = -1$  is called the magnetic

susceptibility. Thus this means that, for a superconductor the susceptibility is negative i.e., a superconductor exhibits perfect diamagnetism.

**Types of superconductors:**

Depending upon their behavior in an external magnetic field, superconductors are divided into two types:

- 1) Type I superconductors and 2) Type II superconductors

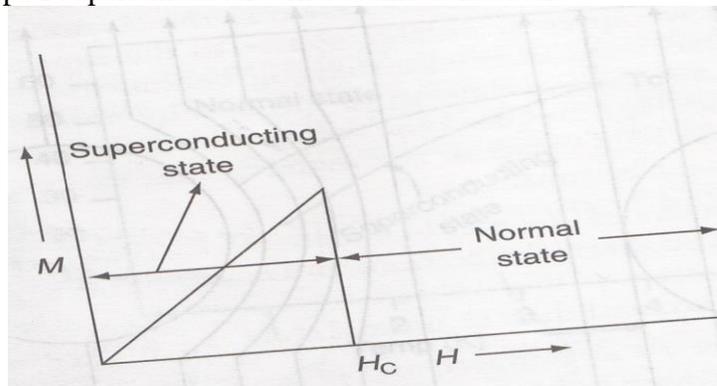
Let us discuss them one by one:

1) **Type I superconductors:**

Those superconductors which lose their superconductivity very easily or abruptly when placed in the external magnetic field are known as Type I superconductors.

**Explanation:**

When the superconductor is kept in the magnetic field and if the field is increased the superconductor becomes a normal conductor abruptly at critical magnetic field as shown in fig. These types of materials are termed as Type – I superconductors. After  $H_c$ , the Type I superconductor will become conductor.



**Fig:** The variation of magnetization (M) with external magnetic field H in a type I Superconductor.

**Properties:**

- These superconductors are also known as **soft superconductors** because of this reason that is they lose their superconductivity easily and relatively small magnetic field requirement to bring them back to their normal state. These superconductors exhibit perfect and complete Meissner effect.
- Only one critical field exists for these superconductors.
- The critical magnetic field value is very low and highest value is 0.1 Tesla.

- No mixed states exist in these superconductors.
- Materials with pure form are Type I superconductors.
- Examples: :

Material	H <sub>c</sub> (Tesla)
Zinc	0.0054
Aluminum	0.0105
Mercury	0.014
Stransiam	0.03
Lead	0.08

## 2) Type II superconductors:

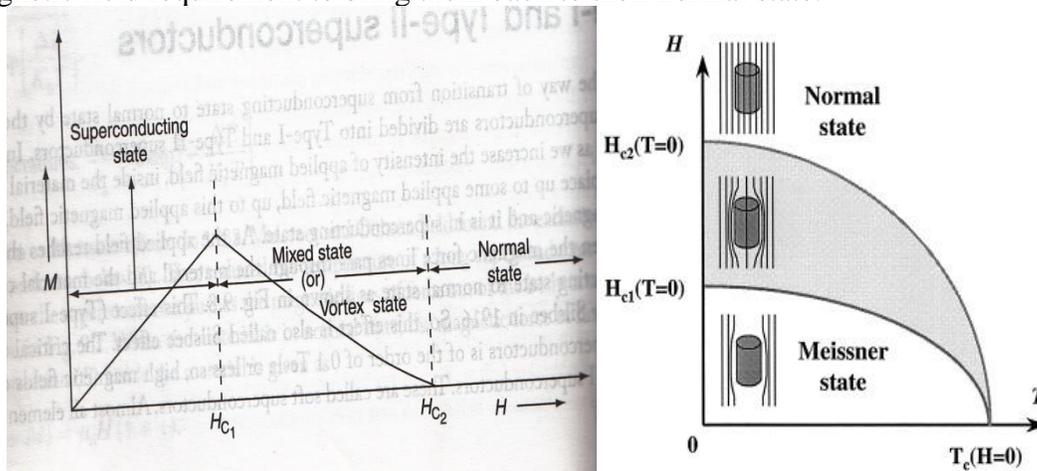
Those superconductors which lose their superconductivity gradually but not easily or abruptly when placed in the external magnetic field are known as Type II superconductors.

### Explanation:

When the super conductor is kept in the magnetic field and if the field is increased, below the lower critical field  $H_{c1}$ , the material exhibits perfect diamagnetism i.e., it behaves as a super conductor and above  $H_{c1}$ , the magnetization decreases and hence the magnetic flux starts penetrating through the material. The specimen is said to be in a mixed state (or) vortex state between  $H_{c1}$  and  $H_{c2}$ , above  $H_{c2}$  (upper critical field) it becomes a normal conductor as shown in fig.

Type – II Super conductors are also called as hard super conductors because of relatively sma

ll magnetic field requirement to bring them back to their normal state.



**Fig:** The variation of magnetization (M) with external magnetic field H in a type II Superconductor.

### Properties:

- These superconductors are also known as **hard superconductors** because of this reason that is they lose their superconductivity gradually but not easily and relatively large magnetic field requirement to bring them back to their normal state.
- These superconductors exhibit Meissner effect but not completely.
- Two critical fields  $H_{c1}$  (lower critical magnetic field) and  $H_{c2}$  (upper critical magnetic field) exist for these superconductors.
- The critical magnetic field value is very high.

- Mixed states exist in these superconductors.
- Materials with impurities or alloys are of Type II superconductors.
- Examples:

Material	H <sub>c</sub> (Tesla)
NbN	8 x 10 <sup>6</sup>
BaBi <sub>3</sub>	59 x 10 <sup>3</sup>
Nb <sub>3</sub> Sn	24.5
Nb <sub>3</sub> Ge	38
Y <sub>1</sub> Ba <sub>2</sub> Cu <sub>3</sub> O <sub>7</sub>	300

**Penetration depth:**

According Meissner effect, when the material is cooled below its critical temperature ( $T \leq T_C$ ) and with  $H \leq H_C$ , then the magnetic lines of forces are expelled or ejected out from the super conducting material .i.e., magnetic field drop to zero at the surface of the super conducting material.

But, in 1935, F. London and H.London observed that the applied magnetic field does not drop to zero at the surface of the super conductor but decreases exponentially as given by the equation.

$$H = H_0 \exp^{-x/\lambda} \dots\dots\dots (1)$$

Where H is the intensity of magnetic field at a depth x from the surface,  
 H<sub>0</sub> is the intensity of magnetic field at the surface,  
 and λ is called London Penetration depth.

To define the penetration depth, in the equation (1), let x = λ. then

$$H = H_0 \exp^{-1}$$

$$H = \frac{H_0}{e} \dots\dots\dots (2)$$

Hence penetration depth can be defined as the distance from the surface of the superconductor to a point inside the material at which the intensity of magnetic field is (1/e) of the magnetic field at the surface [i.e., H<sub>0</sub>/e].

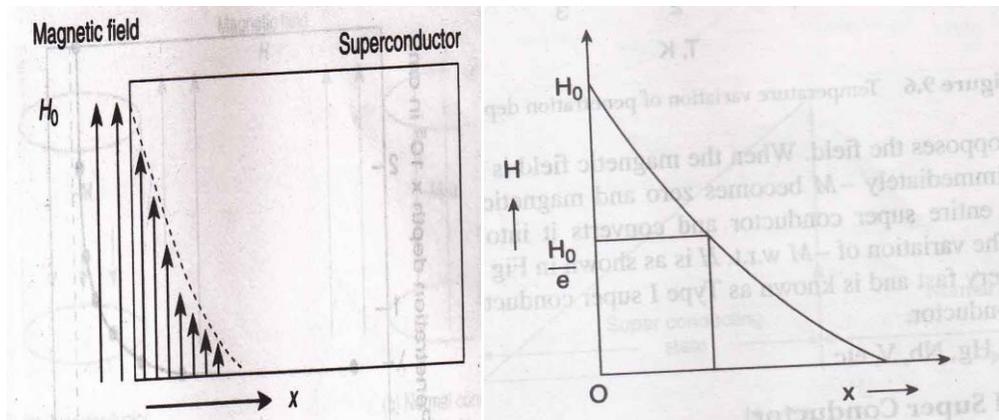


Fig: London penetration depth

The magnetic field is likely to penetrate to a depth of 10 to 100nm from the surface of a superconductor. The value of λ for some materials is given below:

Material	$\lambda$ (in nm)
Mercury	70
Aluminum	50
Tin	50
Lead	39
Indium	64

**Flux Quantization:**

The quantization of magnetic flux is a special property of superconductors.

We know that electric charge is quantized in terms of integral multiples of charge on an electron.

$$Q = \pm ne$$

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

Similarly, the magnetic flux ( $\Phi$ ) lines passing through a super conducting ring due to persistent current is quantized in terms of integral multiples of  $\frac{h}{2e}$

$$\Phi = \frac{nh}{2e}$$

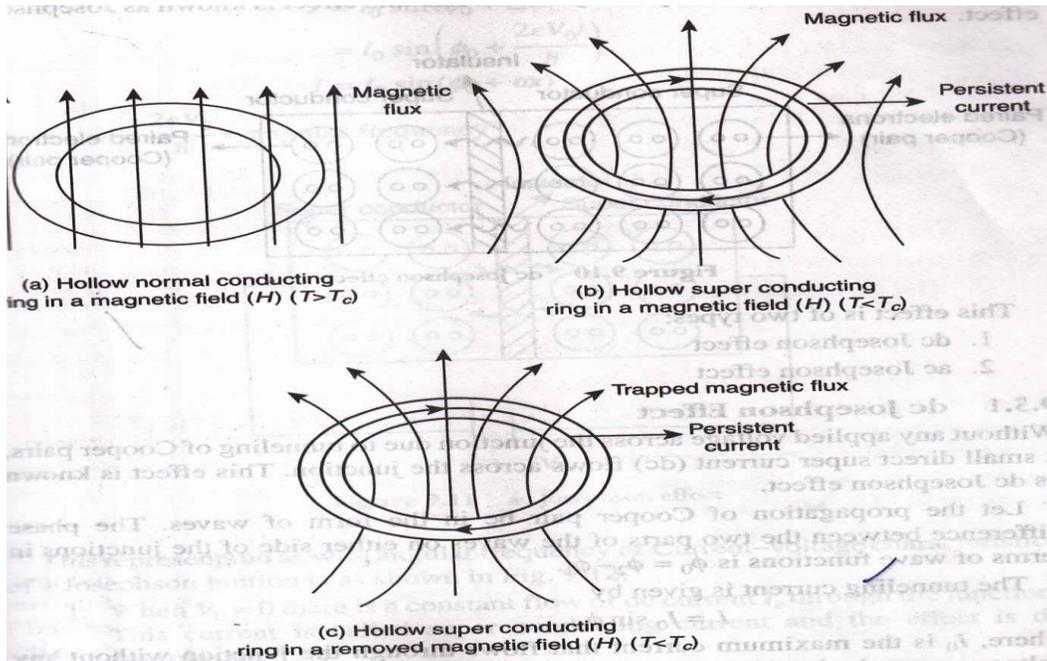
Where  $n = 1, 2, 3, \dots$

Where  $\frac{h}{2e}$  is known as fluxion (or) fluxiod. =  $2.07 \times 10^{-15}$  Weber's.

This phenomenon is known as flux quantization of super conductor.

**Explanation:**

Consider a hollow normal conducting ring in a magnetic field. It allows the magnetic flux due to this field. So, we observe magnetic flux outside and inner hollow space and also on the ring as shown in fig.



When the temperature of the ring is lowered to its critical temperature ( $T_C$ ); the ring expels the magnetic flux and it becomes a super conductor.

As a result, persistent current is set up in the material; this current will remain in the material even if we remove the applied magnetic field afterwards. This persistent current sets up magnetic force lines (i.e., flux) in the ring. This magnetic flux adjusts itself such that the total flux through the cylinder is quantized in integral multiples of  $\frac{h}{2e}$ .

$$\Phi = \frac{nh}{2e}$$

Where  $\frac{h}{2e}$  is known as fluxion (or) fluxiod. =  $2.07 \times 10^{-15}$  Weber's.

This phenomenon is known as flux quantization of super conductor.

**Occurrence of superconductivity:**

**Bardeen, cooper and Schrieffer (BCS) theory:** This is the first microscopic theory, based on quantum mechanics. In 1957 John Bardeen, Leon Cooper, and John Robert Schrieffer wrote a paper called 'Theories of Superconductivity'.

**Principle:**

**According to this theory, superconductivity occurs due to the movement of electron pairs called cooper pairs through the lattice points. These cooper pairs are formed due to electron-lattice –electron interaction.**

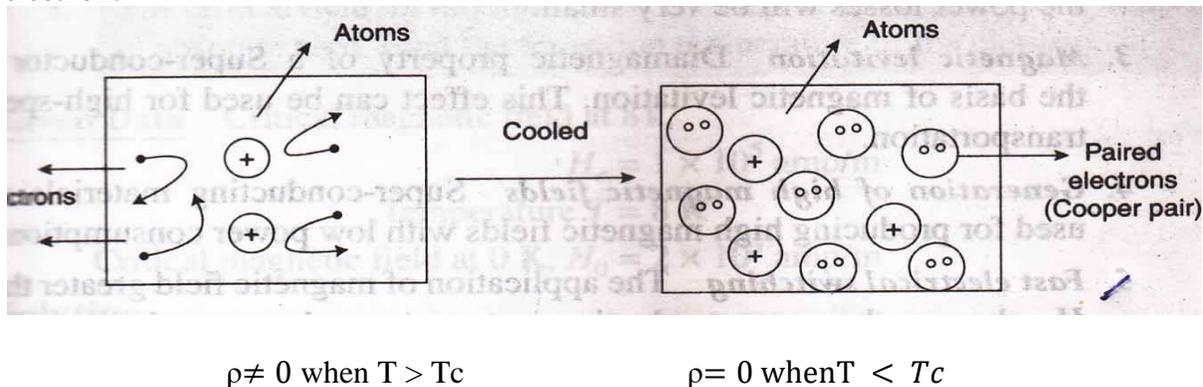
**In this interaction, electrons experience a special kind of attractive interaction, overcoming the coulomb forces of repulsion between them. As result cooper pairs (electron pairs) are formed. At low temperature, these pairs move without scattering through the lattice points and as result resistance or resistivity decreases (i.e., conductivity increases).**

**Explanation:**

Under normal condition, the ions in the lattice vibrate about their equilibrium positions due to thermal energy. These vibrations are lattice vibrations.

When electrons pass through the lattice ions in the normal state, they collide and scatter with the lattice and with each other. As a result, resistance arises in the material.

When the temperature decreases below its critical temperature, due to decrease in energy the scattering of electrons by vibrating lattice ions also decreases. As a result, electron pairs (cooper pairs) are formed. These cooper pairs move without scattering through the lattice ions and as result resistance or resistivity decreases (i.e., conductivity increases) and material becomes superconductor. **These cooper pairs are formed due to electron-lattice – electron.**



**Fig: (a) scattering of electrons in normal state ( $T > T_c$ ), b) movement of cooper pairs without scattering in superconducting sate ( $T < T_c$ ).**

**Formation of cooper pairs:**

### Electron-Lattice (phonon) - Electron interaction:

According to BCS theory,

Suppose an electron (1<sup>st</sup> electron) moves through the lattice, it will be attracted by the positive ion core. It suffers attractive coulomb interaction. . Due to this attraction, positive ion core is disturbed and it is called as lattice distortion. This is shown in the figure below. The lattice vibrations are quantized in terms of phonons.

At that instant, if another electron (2<sup>nd</sup> electron) moves through the distorted lattice, it will be attracted by the greater concentration of positive ion core. It also suffers attractive coulomb interaction.

Therefore, the two electrons interact via lattice distortion or the phonon field, lowering the energy of electrons. This lowering of energy implies that the force between the two electrons is attractive. This type of interaction is called electron-lattice-electron interaction. This interaction can also be interpreted as electron –electron interaction through phonons.

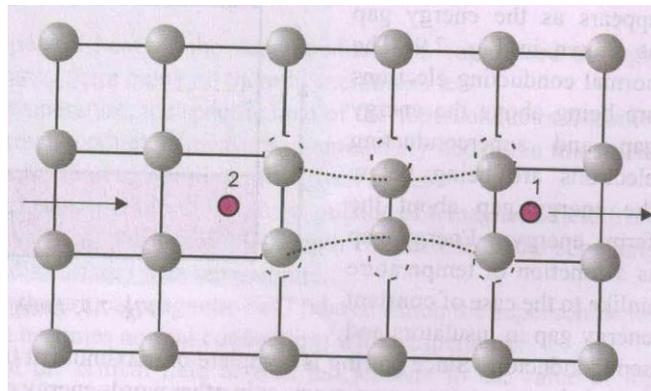
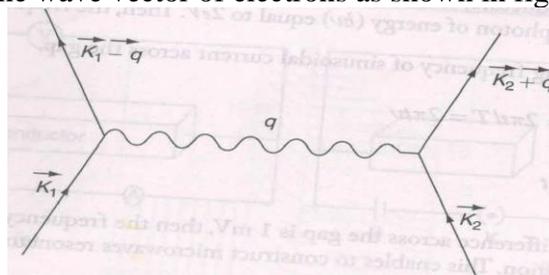


Fig:Electron-Lattice (phonon) - Electron interaction

### Copper Pairs:

Cooper showed that the pair of electrons formed by the interaction between the electrons with opposite spins and momenta are known as cooper pairs. This interaction can be represented in terms of the wave vector of electrons as shown in fig.



Consider the 1<sup>st</sup> electron with wave vector  $\mathbf{k}$  distorts the lattice, there by emitting a phonon of wave vector  $\mathbf{q}$ . This results in the wave vector for  $\mathbf{k}-\mathbf{q}$  for the 1<sup>st</sup> electron.

Now, if the 2<sup>nd</sup> electron with wave vector  $\mathbf{k}^I$ , seeks the lattice, it takes up the energy from the lattice and wave vector changes to  $\mathbf{k}^I + \mathbf{q}$  as shown in fig.

Two electrons with wave vectors  $\mathbf{k}-\mathbf{q}$  and  $\mathbf{k}^I + \mathbf{q}$  form a pair of electrons known as cooper pairs.

**Therefore, the pair of electrons formed due to electron-lattice-electron (force of attraction) by overcoming the electron-electron (force of repulsion), with equal and opposite momentum and spins with wave vectors  $\mathbf{k}-\mathbf{q}$  and  $\mathbf{k}^I + \mathbf{q}$ , and are called cooper .**

### Josephson Effect:

When two super conductors are separated by a very thin insulator (oxide layer of about  $20\text{\AA}$ ), forms a Joseph junction and then cooper pairs can tunnel or penetrates through the thin insulator and constitute a small super current .This effect is called Josephson Effect.

**Explanation:**

Consider two superconductors which are joined together with help of a thin insulating layer and forms a junction called josephson junction. These super conductors consist of paired electrons known as cooper pairs in the superconducting state. These cooper pairs will try to penetrate or tunnel through the thin insulator and constitute a small super current as shown in fig.

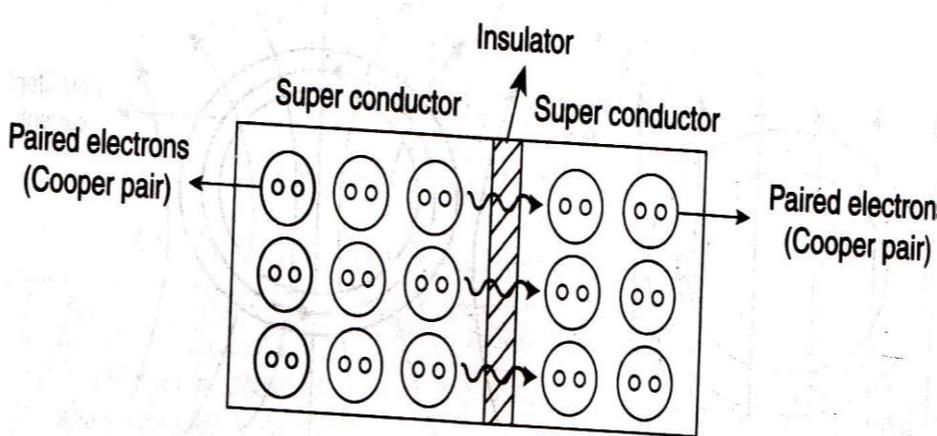


Fig: D.C. Josephson effect

Josephson Effect can be divided into two types .They are:

- a) D.C. Josephson Effect
- b) A.C. Josephson Effect.

**D.C. Josephson Effect:**

Josephson observed that the cooper pairs can tunnel from one film of superconductor into another through the thin insulator and a small direct super current flows across the junction without applied voltage across the junction. This effect is known as D.C. Josephson Effect. Josephson showed that the dc current through the in junction is given by

$$I = I_0 \sin \Phi_0 \dots \dots \dots (1)$$

Where  $\Phi_0 = \Phi_2 - \Phi_1$  is the phase difference the wave functions describing cooper pairs on both sides of the barrier, and  $I_0$  is the critical current which the junction can support and is dependent on the thickness and width of the insulating layer.

**A.C. Josephson Effect:**

If we apply the voltage across the junction, then ac current is produced and is given by

$$I = I_0 \sin (\omega t + \Phi) \dots \dots \dots (2)$$

Where  $\omega =$  angular frequency  $= \frac{4\pi eV}{h}$

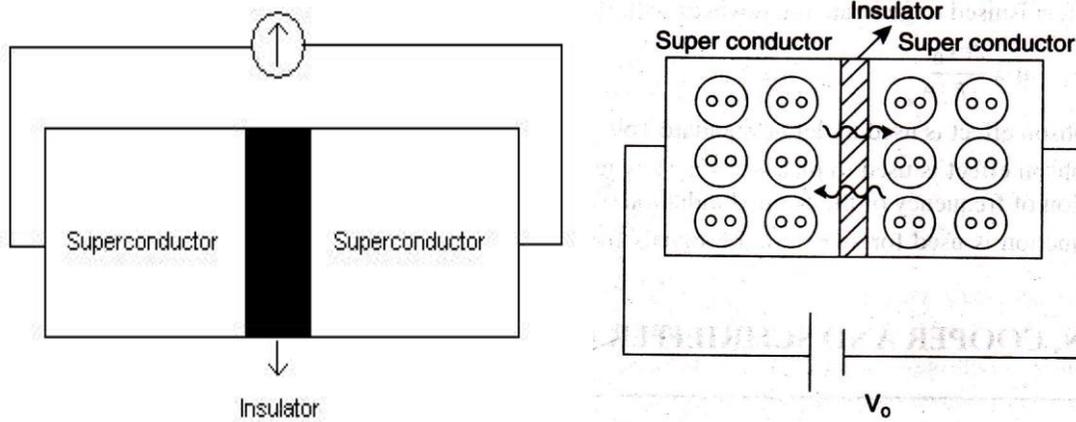


Fig: A.C. Josephson effect

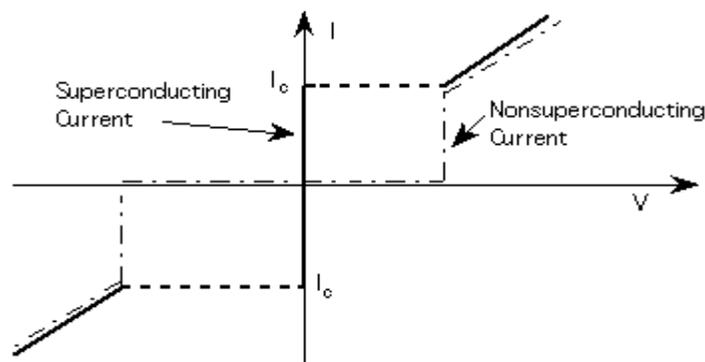


Fig: I-V characteristics of a Josephson junction

### Applications:

Superconductors are used in the following applications:

#### 1. Magnetic Levitation

**Magnetic levitation, maglev, or magnetic suspension** is a method by which an object is suspended with no support other than magnetic fields.

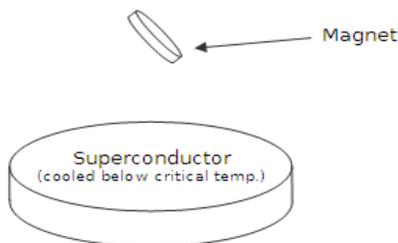


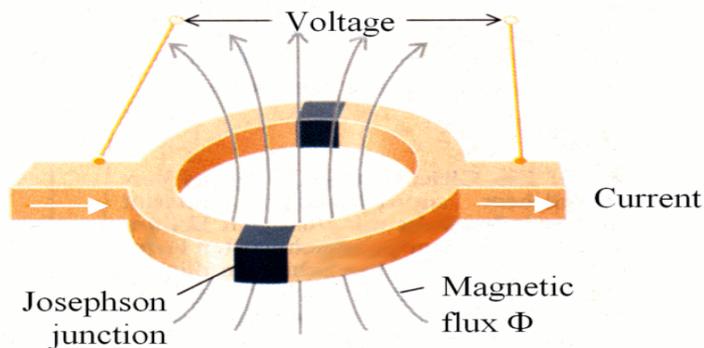
Fig: Maglev train

Magnetic levitation is used for high speed transportation.

For example, Maglev (magnetic levitation) trains travel 500 km/h. These work because a superconductor repels a magnetic field so a magnet will float above a superconductor (Meissner effect)— this virtually eliminates the friction between the train and the track.

### 2.SQUID :

The superconducting quantum interference device (SQUID) consists of two superconductors separated by thin insulating layers to form two parallel Josephson junctions as shown fig.



#### Uses:

- This device used as sensitive magnetometer to detect small magnetic fields from brain and heart.

Threshold for SQUID:  $10^{-14}$

Magnetic field of heart:  $10^{-10}$  T

Magnetic field of brain:  $10^{-13}$  T . .

- They are used in mine detection equipment to help in the removal of land mines.

#### 3. Large hadron collider or particle accelerator:

This use of superconductors was developed at the Rutherford Appleton Laboratory in Oxfordshire, UK in the 1960s. The latest and biggest large hadron collider is currently being built in Switzerland by a coalition of scientific organizations from several countries. Superconductors are used to make extremely powerful electromagnets to accelerate charged particles very fast (to near the speed of light).

#### 4. Magnetic Resonance Imaging (MRI)

MRI is a technique developed in the 1940s that allows doctors to see what is happening inside the body without directly performing surgery.

Fig: MRI scan of a human skull

#### 5. Efficient

#### Electricity

#### Transportation:

Superconducting magnets are also more efficient in generating electricity than conventional copper wire generators - in fact, a superconducting generator about half the size of a copper wire generator is about 99% efficient; typical generators are around 50% efficient.

# NANOMATERIALS

## 1. Introduction

Nanomaterials are cornerstones of nanoscience and nanotechnology. Nanostructure science and technology is a broad and interdisciplinary area of research and development activity that has been growing explosively worldwide in the past few years. It has the potential for revolutionizing the ways in which materials and products are created and the range and nature of functionalities that can be accessed. It is already having a significant commercial impact, which will assuredly increase in the future.

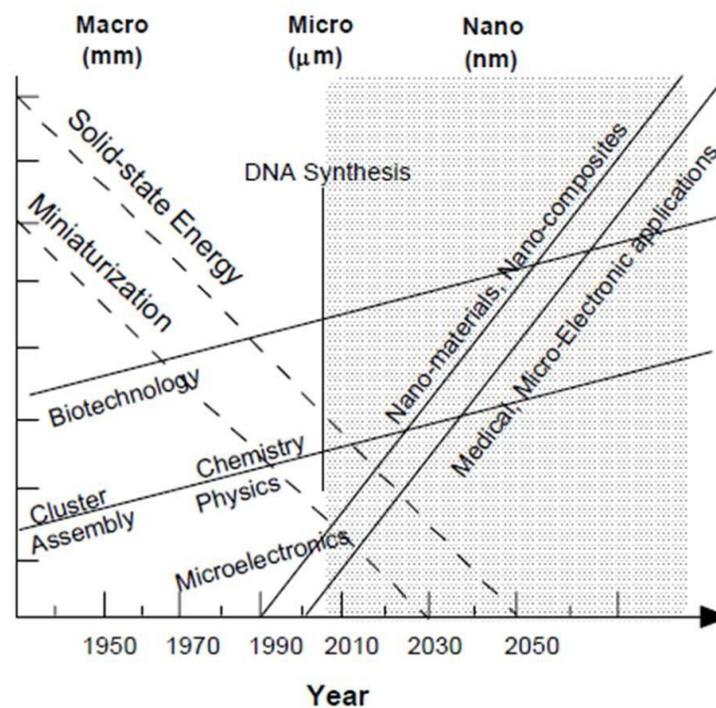


Fig. 1. Evolution of science and technology and the future

## What are nanomaterials?

Nanoscale materials are defined as a set of substances where at least one dimension is less than approximately 100 nanometers. A nanometer is one millionth of a millimeter - approximately 100,000 times smaller than the diameter of a human hair. Nanomaterials

are of interest because at this scale unique optical, magnetic, electrical, and other properties emerge. These emergent properties have the potential for great impacts in electronics, medicine, and other fields.



Fig. 2. Nanomaterial (For example: Carbon nanotube)

## 2. Classification of Nanomaterials

Nanomaterials have extremely small size which having at least one dimension 100 nm or less. Nanomaterials can be nanoscale in one dimension (eg. surface films), two dimensions (eg. strands or fibres), or three dimensions (eg. particles). They can exist in single, fused, aggregated or agglomerated forms with spherical, tubular, and irregular shapes. Common types of nanomaterials include nanotubes, dendrimers, quantum dots and fullerenes. Nanomaterials have applications in the field of nano technology, and displays different physical chemical characteristics from normal chemicals (i.e., silver nano, carbon nanotube, fullerene, photocatalyst, carbon nano, silica).

According to Siegel, Nanostructured materials are classified as Zero dimensional, one dimensional, two dimensional, three dimensional nanostructures.

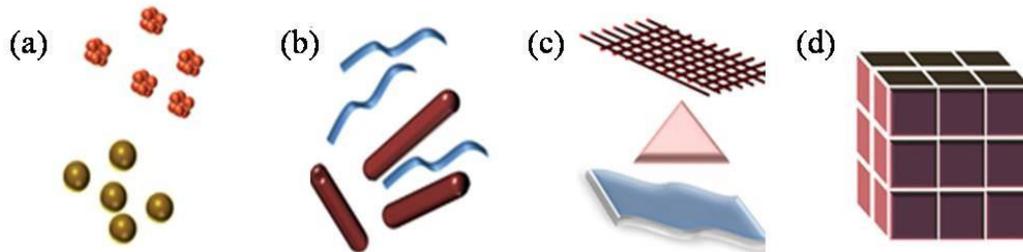
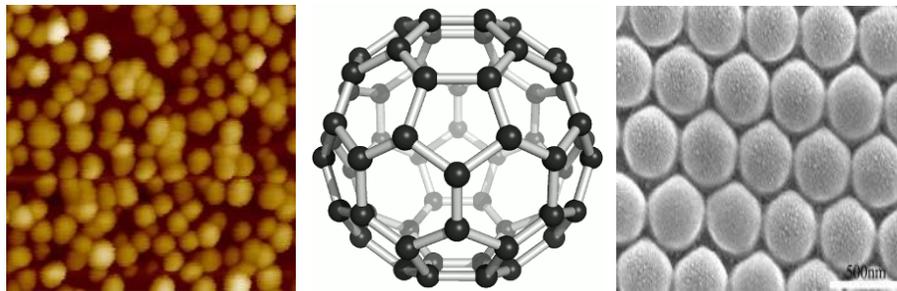


Fig. 3. Classification of Nanomaterials (a) 0D spheres and clusters, (b) 1D nanofibers, wires, and rods, (c) 2D films, plates, and networks, (d) 3D nanomaterials.

Nanomaterials are materials which are characterized by an ultra fine grain size ( $< 50 \text{ nm}$ ) or by a dimensionality limited to  $50 \text{ nm}$ . Nanomaterials can be created with various modulation dimensionalities as defined by Richard W. Siegel: zero (atomic clusters, filaments and cluster assemblies), one (multilayers), two (ultrafine-grained overlayers or buried layers), and three (nanophase materials consisting of equiaxed nanometer sized grains) as shown in the above figure 3.

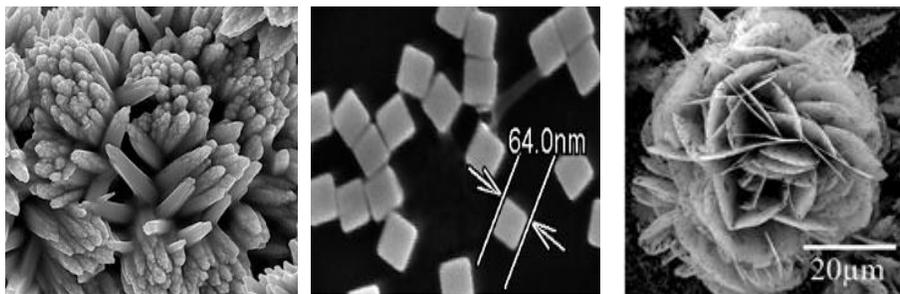
### 3. Examples of Nanomaterials

Nanomaterials (gold, carbon, metals, meta oxides and alloys) with variety of morphologies (shapes) are depicted in Fig. 4.



Au nanoparticle

Buckminsterfullerene FePt nanosphere



Titanium nanoflower

Silver nanocubes

SnO2 nanoflower

Fig. 4. Nanomaterials with a variety of morphologies

#### 4. Nanomaterial - synthesis and processing

Nanomaterials deal with very fine structures: a nanometer is a billionth of a meter. This indeed allows us to think in both the ‘bottom up’ or the ‘top down’ approaches (Fig. 5) to synthesize nanomaterials, i.e. either to assemble atoms together or to dis-assemble (break, or dissociate) bulk solids into finer pieces until they are constituted of only a few atoms. This domain is a pure example of interdisciplinary work encompassing physics, chemistry, and engineering upto medicine.

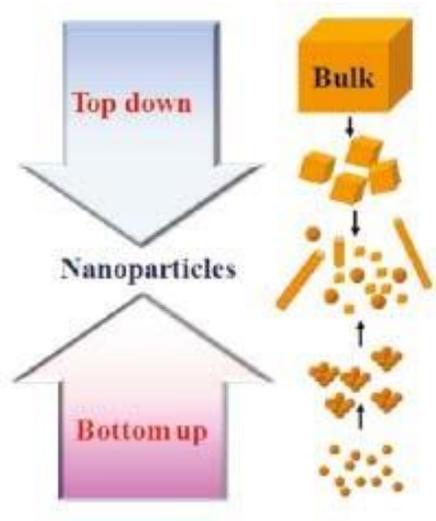


Fig. 5. Schematic illustration of the preparative methods of nanoparticles.

#### Methods for creating nanostructures

There are many different ways of creating nanostructures: of course, macromolecules or nanoparticles or buckyballs or nanotubes and so on can be synthesized artificially for certain specific materials. They can also be arranged by methods based on equilibrium or near-equilibrium thermodynamics such as methods of self-organization and self-assembly (sometimes also called bio-mimetic processes). Using these methods, synthesized materials can be arranged into useful shapes so that finally the material can be applied to a certain application.

#### Mechanical grinding-Ball Milling Method

Mechanical attrition is a typical example of ‘top down’ method of synthesis of nanomaterials, where the material is prepared not by cluster assembly but by the

structural decomposition of coarser-grained structures as the result of severe plastic deformation. This has become a popular method to make nanocrystalline materials because of its simplicity, the relatively inexpensive equipment needed, and the applicability to essentially the synthesis of all classes of materials. The major advantage often quoted is the possibility for easily scaling up to tonnage quantities of material for various applications. Similarly, the serious problems that are usually cited are;

1. contamination from milling media and/or atmosphere, and
2. to consolidate the powder product without coarsening the nanocrystalline microstructure.

In fact, the contamination problem is often given as a reason to dismiss the method, at least for some materials. Here we will review the mechanisms presently believed responsible for formation of nanocrystalline structures by mechanical attrition of single phase powders, mechanical alloying of dissimilar powders, and mechanical crystallisation of amorphous materials. The two important problems of contamination and powder consolidation will be briefly considered.

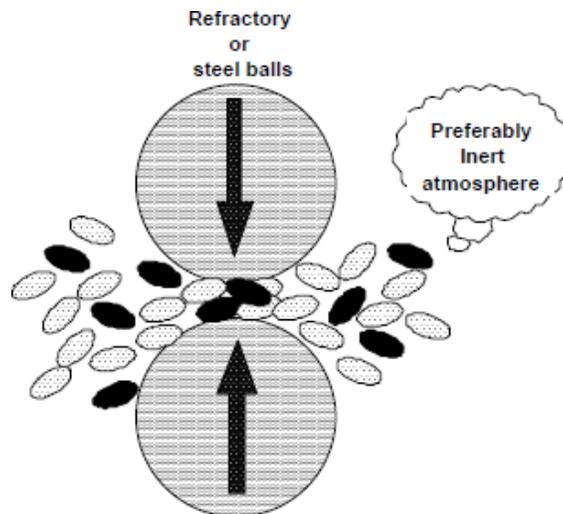


Fig. 6. Schematic representation of the principle of mechanical milling

Mechanical milling is typically achieved using high energy shaker, planetary ball, or tumbler mills. The energy transferred to the powder from refractory or steel balls depends on the rotational (vibrational) speed, size and number of the balls, ratio of the ball to

powder mass, the time of milling and the milling atmosphere. Nanoparticles are produced by the shear action during grinding.

Milling in cryogenic liquids can greatly increase the brittleness of the powders influencing the fracture process. As with any process that produces fine particles, an adequate step to prevent oxidation is necessary. Hence this process is very restrictive for the production of non-oxide materials since then it requires that the milling take place in an inert atmosphere and that the powder particles be handled in an appropriate vacuum system or glove box. This method of synthesis is suitable for producing amorphous or nanocrystalline alloy particles, elemental or compound powders. If the mechanical milling imparts sufficient energy to the constituent powders a homogeneous alloy can be formed. Based on the energy of the milling process and thermodynamic properties of the constituents the alloy can be rendered amorphous by this processing.

### **Wet Chemical Synthesis of Nanomaterials**

In principle we can classify the wet chemical synthesis of nanomaterials into two broad groups:

1. The top down method: where single crystals are etched in an aqueous solution for producing nanomaterials, For example, the synthesis of porous silicon by electrochemical etching.
2. The bottom up method: consisting of sol-gel method, precipitation etc. where materials containing the desired precursors are mixed in a controlled fashion to form a colloidal solution.

### **Chemical Vapour Deposition Method**

As shown schematically in Figure, the evaporative source used in GPC is replaced by a hot wall reactor in the Chemical Vapour Condensation or the CVC process. Depending on the processing parameters nucleation of nanoparticles is observed during chemical vapour deposition (CVC) of thin films and poses a major problem in obtaining good film qualities. The original idea of the novel CVC process which is schematically shown below where, it was intended to adjust the parameter field during the synthesis in order to suppress film formation and enhance homogeneous nucleation of particles in the gas flow. It is readily found that the residence time of the precursor in the reactor determines if films or particles are formed. In a certain range of residence time both particle and film formation can be obtained.

Adjusting the residence time of the precursor molecules by changing the gas flow rate, the pressure difference between the precursor delivery system and the main chamber occurs. Then the temperature of the hot wall reactor results in the fertile production of nanosized particles of metals and ceramics instead of thin films as in CVD processing. In the simplest form a metal organic precursor is introduced into the hot zone of the reactor using mass flow controller. Besides the increased quantities in this continuous process compared to GPC has been demonstrated that a wider range of ceramics including nitrides and carbides can be synthesised. Additionally, more complex oxides such as  $\text{BaTiO}_3$  or composite structures can be formed as well. Appropriate precursor compounds can be readily found in the CVD literature. The extension to production of nanoparticles requires the determination of a modified parameter field in order to promote particle formation instead of film formation. In addition to the formation of single phase nanoparticles by CVC of a single precursor the reactor allows the synthesis of

1. mixtures of nanoparticles of two phases or doped nanoparticles by supplying two precursors at the front end of the reactor, and
2. coated nanoparticles, i.e.,  $n\text{-ZrO}_2$  coated with  $n\text{-Al}_2\text{O}_3$  or vice versa, by supplying a second precursor at a second stage of the reactor. In this case nanoparticles which have been formed by homogeneous nucleation are coated by heterogeneous nucleation in a second stage of the reactor.

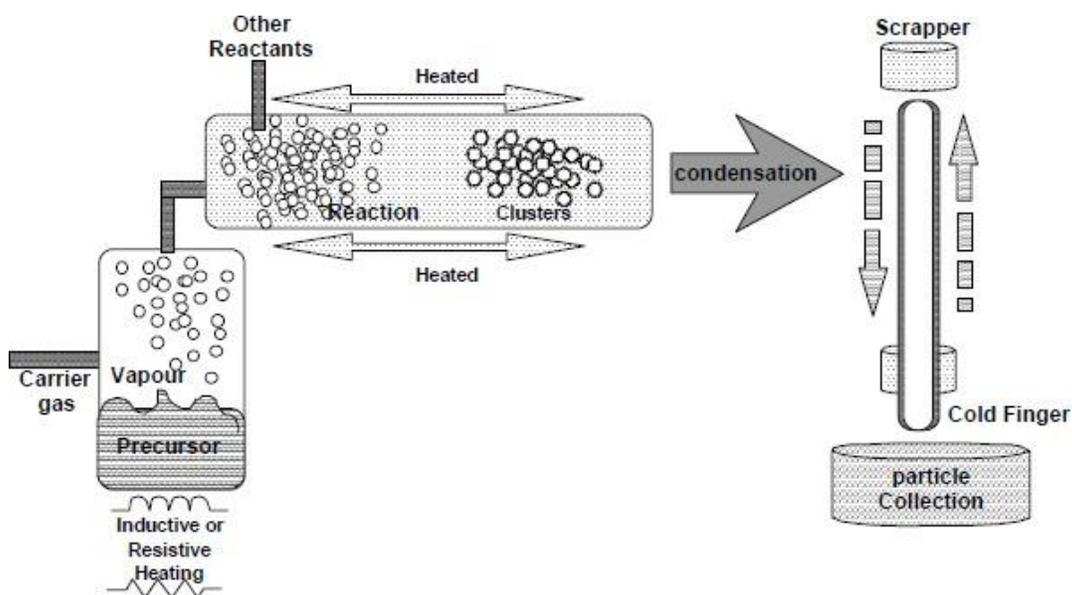


Fig. 11. A schematic of a typical CVC reactor

Because CVC processing is continuous, the production capabilities are much larger than in GPC processing. Quantities in excess of 20 g/hr have been readily produced with a small scale laboratory reactor. A further expansion can be envisaged by simply enlarging the diameter of the hot wall reactor and the mass flow through the reactor.

## 7. Properties of Nanomaterials

Nanomaterials have the structural features in between of those of atoms and the bulk materials. While most microstructured materials have similar properties to the corresponding bulk materials, the properties of materials with nanometer dimensions are significantly different from those of atoms and bulks materials. This is mainly due to the nanometer size of the materials which render them: (i) large fraction of surface atoms; (ii) high surface energy; (iii) spatial confinement; (iv) reduced imperfections, which do not exist in the corresponding bulk materials.

Due to their small dimensions, nanomaterials have extremely large surface area to volume ratio, which makes a large to be the surface or interfacial atoms, resulting in more “surface” dependent material properties. Especially when the sizes of nanomaterials are comparable to length, the entire material will be affected by the surface properties of nanomaterials. This in turn may enhance or modify the properties of the bulk materials. For example, metallic nanoparticles can be used as very active catalysts. Chemical sensors from nanoparticles and nanowires enhanced the sensitivity and sensor selectivity. The nanometer feature sizes of nanomaterials also have spatial confinement effect on the materials, which bring the quantum effects.

The energy band structure and charge carrier density in the materials can be modified quite differently from their bulk and in turn will modify the electronic and optical properties of the materials. For example, lasers and light emitting diodes (LED) from both of the quantum dots and quantum wires are very promising in the future optoelectronics. High density information storage using quantum dot devices is also a fast developing area. Reduced imperfections are also an important factor in determination of the properties of the nanomaterials. Nanosturctures and Nanomaterials favors of a self-purification process in that the impurities and intrinsic material defects will move to near the surface upon thermal annealing. This increased materials perfection affects the properties of nanomaterials. For example, the chemical stability for certain nanomaterials may be enhanced, the mechanical properties of nanomaterials will be better than the bulk

materials. The superior mechanical properties of carbon nanotubes are well known. Due to their nanometer size, nanomaterials are already known to have many novel properties. Many novel applications of the nanomaterials rose from these novel properties have also been proposed.

### Optical properties

One of the most fascinating and useful aspects of nanomaterials is their optical properties. Applications based on optical properties of nanomaterials include optical detector, laser, sensor, imaging, phosphor, display, solar cell, photocatalysis, photoelectrochemistry and biomedicine.

The optical properties of nanomaterials depend on parameters such as feature size, shape, surface characteristics, and other variables including doping and interaction with the surrounding environment or other nanostructures. Likewise, shape can have dramatic influence on optical properties of metal nanostructures. Fig. ( ) exemplifies the difference in the optical properties of metal and semiconductor nanoparticles. With the CdSe semiconductor nanoparticles, a simple change in size alters the optical properties of the nanoparticles. When metal nanoparticles are enlarged, their optical properties change only slightly as observed for the different samples of gold nanospheres in fig. ( ). However, when an anisotropy is added to the nanoparticle, such as growth of nanorods, the optical properties of the nanoparticles change dramatically.

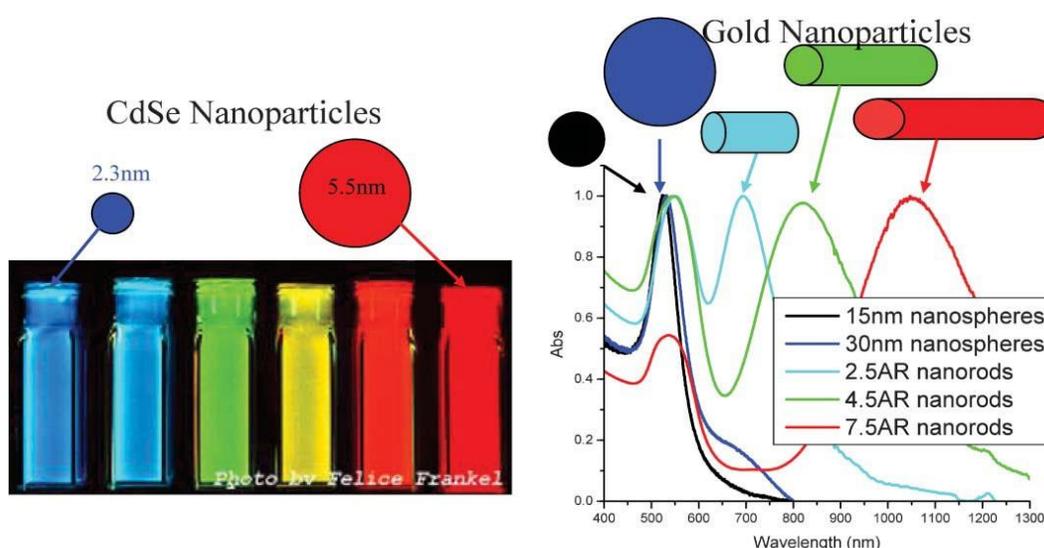


Fig. 13. Fluorescence emission of (CdSe) ZnS quantum dots of various sizes and absorption spectra of various sizes and shapes of gold nanoparticles (Chem. Soc. Rev., 2006, 35, 209–217).

### **Mechanical properties**

“Mechanical Properties of Nanoparticles” deals with bulk metallic and ceramic materials, influence of porosity, influence of grain size, superplasticity, filled polymer composites, particle-filled polymers, polymer-based nanocomposites filled with platelets, carbon nanotube-based composites. The discussion of mechanical properties of nanomaterials is, in to some extent, only of quite basic interest, the reason being that it is problematic to produce macroscopic bodies with a high density and a grain size in the range of less than 100 nm. However, two materials, neither of which is produced by pressing and sintering, have attracted much greater interest as they will undoubtedly achieve industrial importance.

These materials are polymers which contain nanoparticles or nanotubes to improve their mechanical behaviors, and severely plastic-deformed metals, which exhibit astonishing properties. However, because of their larger grain size, the latter are generally not accepted as nanomaterials. Experimental studies on the mechanical properties of bulk nanomaterials are generally impaired by major experimental problems in producing specimens with exactly defined grain sizes and porosities. Therefore, model calculations and molecular dynamic studies are of major importance for an understanding of the mechanical properties of these materials.

Filling polymers with nanoparticles or nanorods and nanotubes, respectively, leads to significant improvements in their mechanical properties. Such improvements depend heavily on the type of the filler and the way in which the filling is conducted. The latter point is of special importance, as any specific advantages of a nanoparticulate filler may be lost if the filler forms aggregates, thereby mimicking the large particles. Particulate-filled polymer-based nanocomposites exhibit a broad range of failure strengths and strains. This depends on the shape of the filler, particles or platelets, and on the degree of agglomeration. In this class of material, polymers filled with silicate platelets exhibit the best mechanical properties and are of the greatest economic relevance. The larger the particles of the filler or agglomerates, the poorer are the properties obtained. Although, potentially, the best composites are those filled with nanofibers or nanotubes, experience teaches that sometimes such composites have the least ductility. On the other hand, by using carbon nanotubes it is possible to produce composite fibers with extremely high strength and strain at rupture. Among the most exciting nanocomposites are the polymer-ceramic nanocomposites, where the ceramic phase is platelet-shaped. This type of composite is preferred in nature, and is found in the structure of bones, where it consists

of crystallized mineral platelets of a few nanometers thickness that are bound together with collagen as the matrix. Composites consisting of a polymer matrix and defoliated phyllosilicates exhibit excellent mechanical and thermal properties.

### Magnetic properties

Bulk gold and Pt are non-magnetic, but at the nano size they are magnetic. Surface atoms are not only different to bulk atoms, but they can also be modified by interaction with other chemical species, that is, by capping the nanoparticles. This phenomenon opens the possibility to modify the physical properties of the nanoparticles by capping them with appropriate molecules. Actually, it should be possible that non-ferromagnetic bulk materials exhibit ferromagnetic-like behavior when prepared in nano range. One can obtain magnetic nanoparticles of Pd, Pt and the surprising case of Au (that is diamagnetic in bulk) from non-magnetic bulk materials. In the case of Pt and Pd, the ferromagnetism arises from the structural changes associated with size effects.

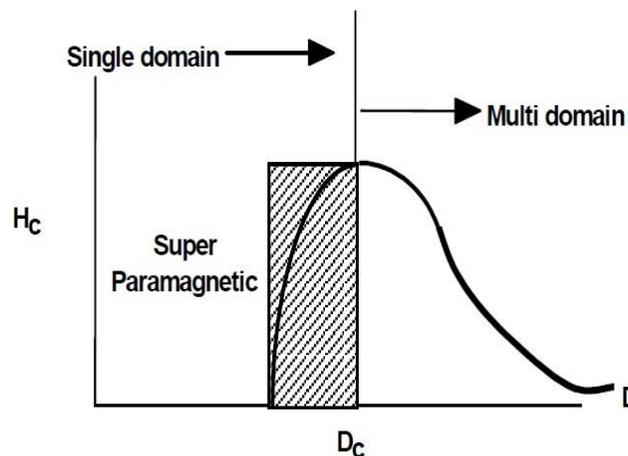


Fig. 15. Magnetic properties of nanostructured materials

However, gold nanoparticles become ferromagnetic when they are capped with appropriate molecules: the charge localized at the particle surface gives rise to ferromagnetic-like behavior.

Surface and the core of Au nanoparticles with 2 nm in diameter show ferromagnetic and paramagnetic character, respectively. The large spin-orbit coupling of these noble metals can yield to a large anisotropy and therefore exhibit high ordering temperatures. More surprisingly, permanent magnetism was observed up to room temperature for thiol-capped Au nanoparticles. For nanoparticles with sizes below 2 nm the localized carriers are in the 5d band. Bulk Au has an extremely low density of states and becomes diamagnetic, as is also the case for bare Au nanoparticles. This observation

suggested that modification of the d band structure by chemical bonding can induce ferromagnetic like character in metallic clusters.

## **8. Selected Application of nanomaterials**

Nanomaterials having wide range of applications in the field of electronics, fuel cells, batteries, agriculture, food industry, and medicines, etc... It is evident that nanomaterials split their conventional counterparts because of their superior chemical, physical, and mechanical properties and of their exceptional formability.

### **Fuel cells**

A fuel cell is an electrochemical energy conversion device that converts the chemical energy from fuel (on the anode side) and oxidant (on the cathode side) directly into electricity. The heart of fuel cell is the electrodes. The performance of a fuel cell electrode can be optimized in two ways; by improving the physical structure and by using more active electro catalyst. A good structure of electrode must provide ample surface area, provide maximum contact of catalyst, reactant gas and electrolyte, facilitate gas transport and provide good electronic conductance. In this fashion the structure should be able to minimize losses.

### **Phosphors for High-Definition TV**

The resolution of a television, or a monitor, depends greatly on the size of the pixel. These pixels are essentially made of materials called "phosphors," which glow when struck by a stream of electrons inside the cathode ray tube (CRT). The resolution improves with a reduction in the size of the pixel, or the phosphors. Nanocrystalline zinc selenide, zinc sulfide, cadmium sulfide, and lead telluride synthesized by the sol-gel techniques are candidates for improving the resolution of monitors. The use of

nanophosphors is envisioned to reduce the cost of these displays so as to render high-definition televisions (HDTVs) and personal computers affordable to be purchase.

### **Next-Generation Computer Chips**

The microelectronics industry has been emphasizing miniaturization, whereby the circuits, such as transistors, resistors, and capacitors, are reduced in size. By achieving a significant reduction in their size, the microprocessors, which contain these components, can run much faster, thereby enabling computations at far greater speeds. However, there are several technological impediments to these advancements, including lack of the ultrafine precursors to manufacture these components; poor dissipation of tremendous amount of heat generated by these microprocessors due to faster speeds; short mean time to failures (poor reliability), etc. Nanomaterials help the industry break these barriers down by providing the manufacturers with nanocrystalline starting materials, ultra-high purity materials, materials with better thermal conductivity, and longer-lasting, durable interconnections (connections between various components in the microprocessors).

#### **Example:** Nanowires for junctionless transistors

Transistors are made so tiny to reduce the size of sub assemblies of electronic systems and make smaller and smaller devices, but it is difficult to create high-quality junctions. In particular, it is very difficult to change the doping concentration of a material over distances shorter than about 10 nm. Researchers have succeeded in making the junctionless transistor having nearly ideal electrical properties. It could potentially operate faster and use less power than any conventional transistor on the market today. The device consists of a silicon nanowire in which current flow is perfectly controlled by a silicon gate that is separated from the nanowire by a thin insulating layer. The entire silicon nanowire is heavily n-doped, making it an excellent conductor. However, the gate is p-doped and its presence has the effect of depleting the number of electrons in the region of the nanowire under the gate. The device also has near-ideal electrical properties and behaves like the most perfect of transistors without suffering from current leakage like conventional devices and operates faster and using less energy.



Fig. 17. Silicon nanowires in junctionless transistors

### Elimination of Pollutants

Nanomaterials possess extremely large grain boundaries relative to their grain size. Hence, they are very active in terms of their chemical, physical, and mechanical properties. Due to their enhanced chemical activity, nanomaterials can be used as catalysts to react with such noxious and toxic gases as carbon monoxide and nitrogen oxide in automobile catalytic converters and power generation equipment to prevent environmental pollution arising from burning gasoline and coal.

### Sun-screen lotion

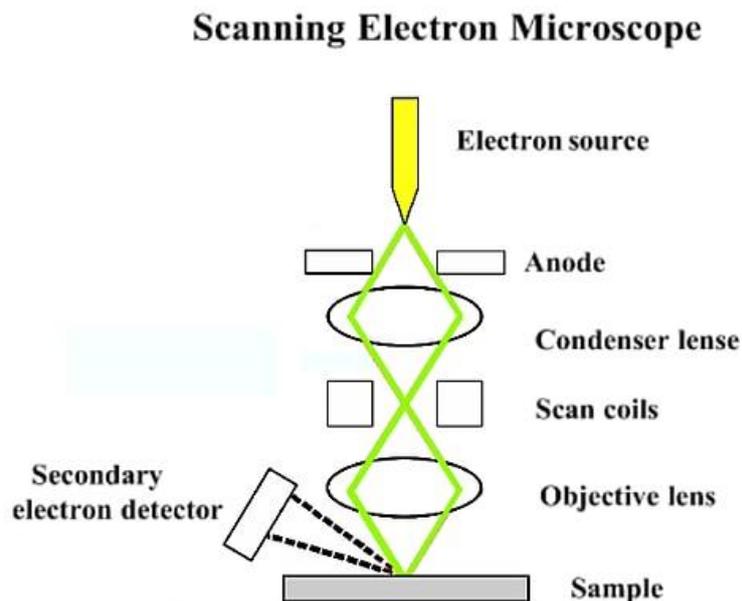
Prolonged UV exposure causes skin-burns and cancer. Sun-screen lotions containing nano-TiO<sub>2</sub> provide enhanced sun protection factor (SPF) while eliminating stickiness. The added advantage of nano skin blocks (ZnO and TiO<sub>2</sub>) arises as they protect the skin by sitting onto it rather than penetrating into the skin. Thus they block UV radiation effectively for prolonged duration. Additionally, they are transparent, thus retain natural skin color while working better than conventional skin-lotions.

### Sensors

Sensors rely on the highly active surface to initiate a response with minute change in the concentration of the species to be detected. Engineered monolayers (few Angstroms thick) on the sensor surface are exposed to the environment and the peculiar functionality (such as change in potential as the CO/anthrax level is detected) is utilized in sensing.

### Scanning Electron Microscopy (SEM)

The scanning electron microscope (SEM) uses a focused beam of high-energy electrons to generate a variety of signals at the surface of solid specimens. The signals that derive from [electron-sample interactions](#) reveal information about the sample including external morphology (texture), chemical composition, and crystalline structure and orientation of materials making up the sample. In most applications, data are collected over a selected area of the surface of the sample, and a 2-dimensional image is generated that displays spatial variations in these properties. Areas ranging from approximately 1 cm to 5 microns in width can be imaged in a scanning mode using conventional SEM techniques (magnification ranging from 20X to approximately 30,000X, spatial resolution of 50 to 100 nm). The SEM is also capable of performing analyses of selected point locations on the sample; this approach is especially useful in qualitatively or semi-quantitatively determining chemical compositions (using [EDS](#)), crystalline structure, and crystal orientations (using [EBSD](#)). The design and function of the SEM is very similar to the [EPMA](#) and considerable overlap in capabilities exists between the two instruments.



Accelerated electrons in an SEM carry significant amounts of kinetic energy, and this energy is dissipated as a variety of signals produced by [electron-sample interactions](#) when the incident electrons are decelerated in the solid sample. These signals include secondary electrons (that produce SEM images), backscattered electrons ([BSE](#)), diffracted

backscattered electrons ([EBSD](#) that are used to determine crystal structures and orientations of minerals), photons ([characteristic X-rays](#) that are used for elemental analysis and continuum X-rays), visible light ([cathodoluminescence--CL](#)), and heat. Secondary electrons and backscattered electrons are commonly used for imaging samples: secondary electrons are most valuable for showing morphology and topography on samples and backscattered electrons are most valuable for illustrating contrasts in composition in multiphase samples (i.e. for rapid phase discrimination). [X-ray generation](#) is produced by inelastic collisions of the incident electrons with electrons in discrete orbitals (shells) of atoms in the sample. As the excited electrons return to lower energy states, they yield X-rays that are of a fixed wavelength (that is related to the difference in energy levels of electrons in different shells for a given element). Thus, characteristic X-rays are produced for each element in a mineral that is "excited" by the electron beam. SEM analysis is considered to be "non-destructive"; that is, x-rays generated by electron interactions do not lead to volume loss of the sample, so it is possible to analyze the same materials repeatedly.

### **X-Ray Diffraction**

X-ray diffraction is the elastic scattering of x-ray photons by atoms in a periodic lattice. The scattered monochromatic x-rays that are in phase give constructive interference. Figure 1 illustrates how diffraction of x-rays by crystal planes allows one to derive lattice spacings by using the Bragg's law.

When a monochromatic X-rays are incident upon a crystal, atoms in different layers acts as a source of scattering radiation of same wavelength. The intensity of the reflected beam will be maximum at certain incident angle when the path difference between two reflected wave from two different planes is an integral multiple of wavelength of X-rays.

i.e For maximum intensity,

$$\text{Path difference} = n\lambda$$

where  $n = 1, 2, 3, \dots$  and  $\lambda = \text{wavelength of X-rays}$

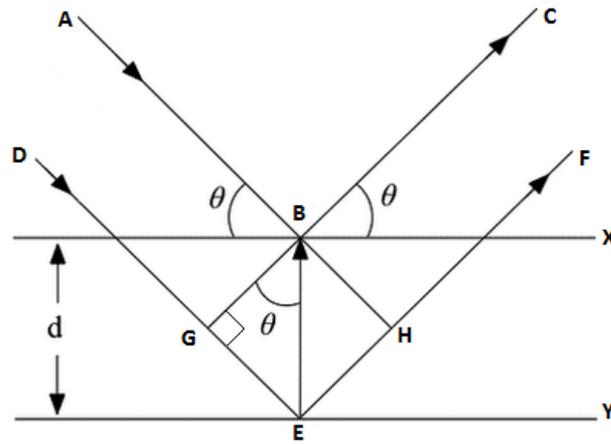


fig: Bragg's Law

Let us consider a parallel beam of monochromatic X-rays  $AB$  and  $DE$  of wavelength  $\lambda$  is incident on parallel crystal planes  $X$  and  $Y$  respectively, both with a equal glancing angle  $\theta$ . Ray  $AB$  strikes an atom at  $B$  and is reflected along  $BC$ . Similarly, ray  $DE$  strikes an atom at  $E$  and is reflected along  $EF$ .

Now, draw  $BG$  and  $BH$  perpendicular to  $DE$  and  $EF$  respectively. From above figure, the path difference between the rays  $DEF$  and  $ABC$  is

$$\text{path difference} = GE + EH$$

From triangle  $BGE$  and  $BEH$ ,

$$EH = GE = BE \sin \theta$$

$$\text{or, } EH = GE = d \sin \theta$$

where  $d$  = interplaner spacing

$$\text{So, path difference} = 2d \sin \theta$$

We know, for maximum intensity

$$\text{Path difference} = n\lambda$$

$$\text{or, } 2d \sin \theta = n\lambda$$

This is called **Bragg's Law**.