

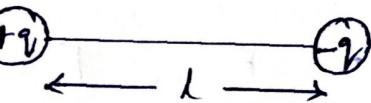
### 3. Dielectric and Magnetic materials

#### Dielectric Materials

##### Basic Definitions :-

(1) Electric dipole :- Two equal and opposite charges separated by a certain distance  $l$  is called Electric Dipole.

Consider two opposite charges of equal magnitudes  $+q$  and  $-q$  separated by a distance  $l$ .



##### Dipole moments (m):

The product of charge and distance between two charges is called dipole moment.

$$m = q \cdot l \text{ columb-meter}$$

where,  $q$  = charge and  $l$  = distance of separation.

##### permittivity ( $\epsilon$ ):

It represents the easily polarisable nature of the dielectric (or) medium.

##### \* Dielectric polarisation (P):

In the presence of an electric field, separation of +ve and -ve charges takes place in a dielectric. Each separated charge acts as a dipole and has a dipole moment i.e. dipoles are induced into the dielectric and it exhibits a net dipole moment in the electric field.

This phenomenon is known as dielectric polarisation.

If "m" is the induced dipole moment and  $v$  is the volume of the dielectric, then polarisation

$$P = \frac{M}{V}$$

It is defined as dipole moment per unit volume in the presence of Electric field.

\* Electric field intensity: force per unit charge or electric flux through unit area of the medium.

$$E = \frac{F}{q}, \quad E = \frac{\phi}{A} = \frac{Q}{A\epsilon_0} \quad [\because \phi = \frac{Q}{\epsilon_0}]$$

\* Dielectric polarisability :-  $\alpha$  :-

The ability of a dielectric to allow its charges to get separated in the presence of an electric field is known as polarisability. The net dipole moment 'P' is proportional to the applied electric field 'E'.

$$P \propto E$$

$$P = \alpha E$$

$$\alpha = \frac{P}{E}, \quad \alpha \text{ is dielectric polarisability}$$

We know that  $P = \frac{M}{V}$

$\text{units} = \text{Farad} - \text{m}^2$

$$P = \frac{\alpha E}{V}$$

\* Dielectric Susceptibility ( $\chi$ ) when an dielectric is placed in an electric field (E) then polarisation takes place.

The polarisation vector P is proportional to electric field

$$P \propto E$$

$$P = \chi E$$

$$\chi = \frac{P}{E}, \quad \text{It has no units}$$

\* Dielectric constant :- ( $\epsilon_r$ )

The dielectric constant of a material is defined as the ratio of the permittivity of the medium ( $\epsilon$ ) to the permittivity of free space ( $\epsilon_0$ ).

$$\epsilon_r = \frac{\epsilon}{\epsilon_0} = \frac{C}{C_0} = \frac{\epsilon_0}{E} = \frac{V_0}{V}$$

- where,
- $C \rightarrow$  Capacitance of capacitor with dielectric
  - $C_0 \rightarrow$  Capacitance of capacitor without dielectric
  - $E \rightarrow$  Intensity of Electric field with dielectric
  - $E_0 \rightarrow$  Intensity of Electric field without dielectric
  - $V \rightarrow$  Potential with dielectric
  - $V_0 \rightarrow$  Potential without dielectric

\* Electric flux density (or) Displacement vector (D) :-

It is defined as the product of intensity of an electric field and permittivity of the medium.

$$D = \epsilon E \rightarrow ①$$

we know that,  $\epsilon_r = \frac{\epsilon}{\epsilon_0}$

$$\epsilon = \epsilon_r \epsilon_0 \rightarrow ②$$

Substitute Eq ② in Eq ①

$D = \epsilon_r \epsilon_0 E$

\* Relation between D, E and P :-

When a dielectric material is placed in a electric field 'E' then polarisation 'P' takes place. The flux density  $D$  is equal to sum of flux density in vaccum, polarisation

of material.

$$D = D_0 + P \rightarrow ①$$

where  $D \rightarrow$  flux density due to applied field.

$D_0 \rightarrow$  flux density without field.

$P \rightarrow$  polarisation.

we have,  $D = \epsilon E$

$$D = \epsilon_0 \epsilon_r E \rightarrow ② \quad [\because \epsilon = \epsilon_r \epsilon_0]$$

and  $D_0 = \epsilon_0 E \rightarrow ③$

Substituting Eq ③ in Eq ①

$$D = \epsilon_0 E + P$$

Substituting Eq ② & ③ in Eq ①

$$\epsilon_0 \epsilon_r E = \epsilon_0 E + P$$

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

$$P = \epsilon_0 E (\epsilon_r - 1) \Rightarrow P = D_0 (\epsilon_r - 1)$$

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

$$\chi = \epsilon_0 (\epsilon_r - 1) \quad [\because \frac{P}{E} = \chi]$$

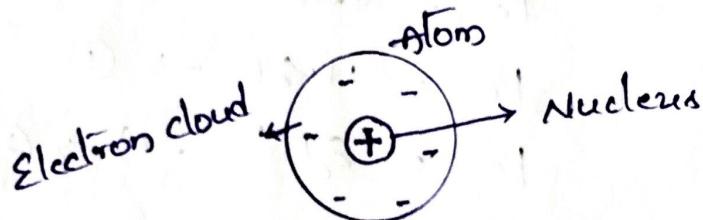
#### \* Types of polarisations :-

Depending upon the type of displaced charges causing polarisation of dielectric in the presence of an electric field, there are 3 types of polarisations.

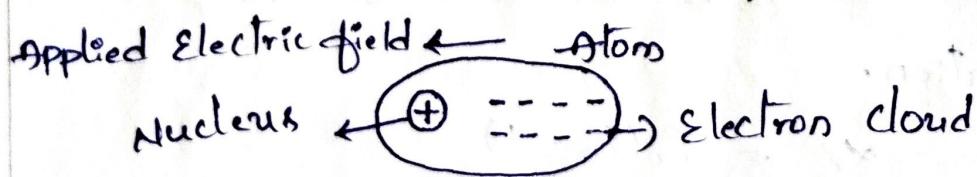
- 1) Electronic polarisation
- 2) Ionic polarisation
- 3) orientation (or) Dipolar polarisation.

(1) Electronic polarisation :-

Consider an atom consisting of a nucleus at the centre and electrons revolving in their orbits. These electrons form an electron cloud surrounding the nucleus. In the absence of an electric field the centres of net +ve and -ve charges coincide, and the atom is not polarised.



When an electric field  $E$  is applied to the atom, displacement of an electron cloud takes place w.r.t the nucleus in a direction opposite to the applied field taking place due to action of electrical force. Now the centres of net +ve and -ve charges do not coincide and it acts as a dipole having dipole moment.



As a result the atom gets polarised. Such type of polarisation due to displacement of Electron cloud in an atom in the presence of an electric field is known as electronic polarisation.

The induced electronic dipole moment is given by

$$\mu_e = \alpha_e E$$

If the atom is spherical with radius 'R' then

$$\alpha_e = 4\pi\epsilon_0 R^3.$$

$\alpha_e$  is depends on the size of the atom.

The induced electronic dipole moment per unit volume is the electronic polarisation  $P_e$ .

If 'N' is the number of atoms per unit volume, then

$$P_e = N\mu_e$$

$$P_e = N\alpha_e E \rightarrow ①$$

$$P_e = \epsilon_0 E (\epsilon_r - 1) \rightarrow ② \quad [\text{from Relation b/w } D, E \text{ & } P]$$

From Eq ① & ②

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

$$\epsilon_r - 1 = \frac{N\alpha_e}{\epsilon_0}$$

$$\epsilon_r = \frac{N\alpha_e}{\epsilon_0} + 1$$

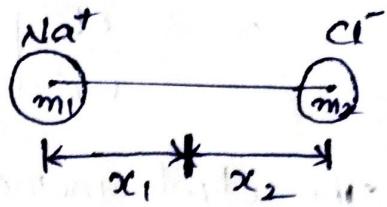
The above equation is dielectric constant due to electronic polarization.

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

From the above equation it is clear that electronic polarization is independent of temperature.

## Ionic polarisation:-

consider a molecule having equal and opposite charges.



Let  $m_1$  and  $m_2$  be the masses of two charges.

when electric field  $E$  is applied, the two charges get displacement in opposite direction

let  $x_1$  and  $x_2$  be the displacement of +ve and -ve charges respectively,

$$\text{The net displacement } x = x_1 + x_2 \rightarrow ①$$

The Lorentz force acting on +ve ion =  $eE$

The Lorentz force acting on -ve ion =  $-eE$

The restoring force acting on +ve ion =  $-k_1 x_1$

The restoring force acting on -ve ion =  $+k_2 x_2$

where  $k_1$  and  $k_2$  restoring constants

At Equilibrium Condition,

for +ve ion :-

$$eE + (-k_1 x_1) = 0$$

$$eE - k_1 x_1 = 0$$

$$eE = k_1 x_1$$

$$x_1 = \frac{eE}{k_1}$$

for -ve ion:-

$$-eE + k_2 x_2 = 0$$

$$eE = k_2 x_2$$

$$x_2 = \frac{eE}{k_2}$$

$$\text{Let } k_1 = m_1 \omega_0^2 \text{ and } k_2 = m_2 \omega_0^2$$

$$\text{The total displacement } x = x_1 + x_2$$

$$x = \frac{eE}{k_1} + \frac{eE}{k_2}$$

$$x = \frac{eE}{m_1 \omega_0^2} + \frac{eE}{m_2 \omega_0^2}$$

$$x = \frac{eE}{\omega_0^2} \left[ \frac{1}{m_1} + \frac{1}{m_2} \right]$$

The dipole moment of ions  $\mu = \text{charge} \times \text{Displacement}$

$$\mu_i = e \times x$$

$$\mu_i = e \cdot \frac{eE}{\omega_0^2} \left[ \frac{1}{m_1} + \frac{1}{m_2} \right]$$

$$\Delta p_i = \frac{e^2}{\omega_0^2} \left[ \frac{1}{m_1} + \frac{1}{m_2} \right] E \rightarrow ④$$

But  $\mu_i \propto E$ .

$$\mu_i = \alpha_i E \rightarrow ⑤$$

Now compare Eq ④ & Eq ⑤, we get.

$$\Delta p_i = \frac{e^2}{\omega_0^2} \left[ \frac{1}{m_1} + \frac{1}{m_2} \right]$$

when the ionic dielectric consists of  $N$  number of ions per unit volume then ionic polarisations is

$$P_i = N \alpha_i E$$

$$P_i = \frac{Ne^2}{\omega_0^2} E \left[ \frac{1}{m_1} + \frac{1}{m_2} \right]$$

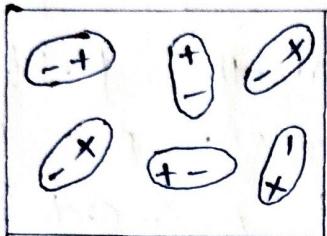
from the above Equation, it is clear that ionic polarisation is independent of temperature.

### Orientation (or) Dipolar polarisation:

Certain molecules will have structure such that it acts as a dipole with permanent dipole moments such molecules are known as polar molecules and the corresponding dielectric is polar dielectric. In the absence of an electric

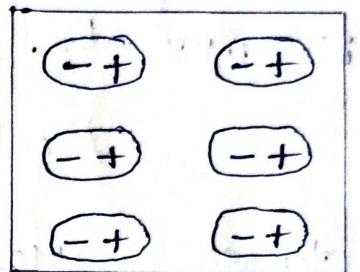
(5)

field the orientations of dipoles are at random due to which no net dipole moment exists and is not polarised.



No Electric field.

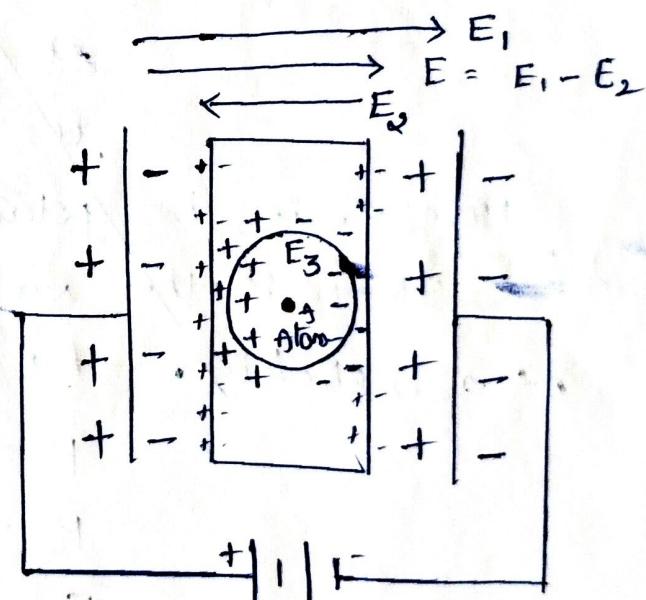
when the electric field is applied the molecule dipoles rotate about their axis of symmetry aligned with the applied field.



Lorentz Internal field (or) Local field :-

The total resultant electric field acting on an atom inside the polarised dielectric is known as Local field (or) internal field.

To find the expression for local field on an atom at point 'a' inside the dielectric, which is placed inside the charged parallel plate capacitor. Now the dielectric is polarised in the electric field across the charged plates. According to



Lorentz method, let us imagine a spherical region with the atom at 'a' as the centre so that spherical region can cover the maximum surface of polarised dielectric.

Let  $E_1$  be the electric field due to charged capacitor,  $E_2$  is the electric field due to induced charges on the dielectric,  $E_3$  is the field due to the dipoles present within in the spherical region,  $E_4$  is the field due to the surface charges on the spherical region. Then the total electric field on an atom at point 'A' inside the dielectric is given by.

$$\text{Local field } E_i = E_1 + E_2 + E_3 + E_4$$

### Clausius - Mosotti Equation :-

The relation between the dielectric constant and the polarisability of a polarised dielectric is known as Clausius - Mosotti Equation.

The induced dipole moment is proportional to  $E_i$ .

$$\mu \propto E_i$$

$$\mu = \alpha E_i$$

Here  $\alpha$  is the polarisability of dielectric.

If  $N$  is the number of atoms per unit volume of a dielectric, then the polarisation is

$$P = N\mu$$

$$P = N\alpha E_i$$

$$E_i = E + \frac{P}{3\epsilon_0}$$

$$P = N\alpha \left[ E + \frac{P}{3\epsilon_0} \right]$$

$$P = N\alpha E + \frac{N\alpha P}{3\epsilon_0}$$

(6)

Let  $E_1$  be the electric field due to charged capacitor.  $E_2$  is the electric field due to induced charges on the dielectric,  $E_3$  is the field due to the dipoles present within the spherical region.  $E_4$  is the field due to the surface charges on the spherical region. Then the total electric field on an atom at point 'i' inside the dielectric is given by.

$$\text{Local field } E_i = E_1 + E_2 + E_3 + E_4$$

$$E_2 = E + E_4 \quad [\text{where as } E_3 = 0]$$

$E$  is the resultant field due to  $E_1$  and  $E_2$  for a cubic structure, due to symmetrical distribution of charges within the spherical region  $E_3 = 0$

$$E_i = E + E_4$$

Calculate  $E_4$  :-

The magnetized view of sphere

$dA$  = unit area of sphere

$$\text{Area of Element } dA = \sigma \pi (PQ)(QR) \rightarrow ①$$

$$\Delta APQ \neq \sin\theta = \frac{PQ}{R}$$

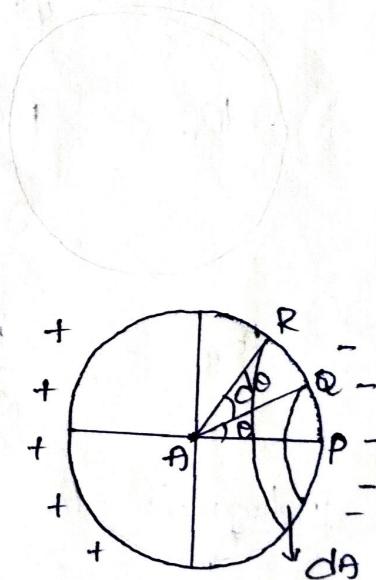
$$\sin\theta = \frac{PQ}{R}$$

$$PQ = R \sin\theta \rightarrow ② \rightarrow$$

Consider  $\Delta AQR$ .

Arc  $\widehat{AQR} = \text{radius} \times \text{angular displacement}$

$$\widehat{AQR} = R\theta \rightarrow ③$$



put Eq ⑤ & ③ in Eq ①.

$$dA = 2\pi(r \sin\theta) (r d\theta)$$

$$dA = 2\pi r^2 \sin\theta d\theta \rightarrow ④$$

The charge  $dq$  on 'da' with x-component

$$dq = p \cos\theta dA \rightarrow ⑤$$

Substitute Eq ④ in Eq ⑤

$$dq = p \cos\theta 2\pi r^2 \sin\theta d\theta$$

$$dq = p 2\pi r^2 \sin\theta \cos\theta d\theta \rightarrow ⑥$$

Field due to charge  $dq$  is denoted by  $dE_4$  at 'a' in the direction of  $\theta = 0^\circ$

$$dE_4 = \frac{dq \cos\theta}{4\pi \epsilon_0 r^2}$$

$$dE_4 = \frac{p (2\pi r^2 \cos\theta \sin\theta) d\theta \cos\theta}{4\pi \epsilon_0 r^2}$$

$$dE_4 = \frac{p \cos^2\theta \sin\theta d\theta}{2\epsilon_0} \rightarrow ⑦$$

Integrate the above Eq.

$$\int_0^{\pi} dE_4 = \frac{p}{2\epsilon_0} \int_0^{\pi} \cos^2\theta \sin\theta d\theta$$

put  $\cos\theta = x$  by differentiating this  $-\sin\theta d\theta = dx$

$$\theta = 0 \text{ then } x = 1$$

$$\sin\theta d\theta = -dx$$

$$\theta = \pi \text{ then } x = -1$$

(7)

$$E_4 = \frac{P}{2\epsilon_0} \int_{-1}^1 x^2 (-dx)$$

$$E_4 = -\frac{P}{2\epsilon_0} \int_{-1}^1 x^2 dx$$

$$E_4 = \frac{P}{2\epsilon_0} \int_{-1}^1 x^2 dx$$

$$E_4 = \frac{P}{2\epsilon_0} \left[ \frac{x^3}{3} \right]_{-1}^1$$

$$E_4 = \frac{P}{2\epsilon_0} \left[ \frac{1}{3} - \left( -\frac{1}{3} \right) \right]$$

$$E_4 = \frac{P}{2\epsilon_0} \left[ \frac{1}{3} + \frac{1}{3} \right]$$

$$E_4 = \frac{P}{2\epsilon_0} \left[ \frac{2}{3} \right]$$

$$E_4 = \frac{P}{3\epsilon_0}$$

$$E_i = E + E_4$$

$$E_i = E + \frac{P}{3\epsilon_0}$$

The above equation is Lorentz field (or) Local field (or) Internal field.

$$E_i = E + \frac{P}{3\epsilon_0}$$

Clausius - Mosotti Equation :-

The relation between the dielectric constant and the polarisability of a polarised dielectric is known as Clausius - Mosotti Equation.

The induced dipole moment is proportional to  $E_i$ .

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Here ' $\alpha$ ' is the polarisability of dielectric.

If  $N$  is the number of atoms per unit volume of a dielectric, then the polarisation is

$$P = N\mu$$

$$P = N\alpha E_i$$

We know, that,  $E_i = E + \frac{P}{3\epsilon_0}$

$$P = N\alpha \left[ E + \frac{P}{3\epsilon_0} \right]$$

$$P = N\alpha E + \frac{N\alpha P}{3\epsilon_0}$$

$$P - \frac{N\alpha P}{3\varepsilon_0} = N\alpha E$$

$$P \left[ 1 - \frac{N\alpha}{3\varepsilon_0} \right] = N\alpha E$$

$$P = \frac{N\alpha E}{\left[ 1 - \frac{N\alpha}{3\varepsilon_0} \right]}$$

$$\text{But, } P = \varepsilon_0 E (\varepsilon_r - 1)$$

$$\varepsilon_0 E (\varepsilon_r - 1) = \frac{N\alpha E}{1 - \frac{N\alpha}{3\varepsilon_0}}$$

$$1 - \frac{N\alpha}{3\varepsilon_0} = \frac{N\alpha E}{\varepsilon_0 E (\varepsilon_r - 1)}$$

$$1 = \frac{N\alpha E}{\varepsilon_0 E (\varepsilon_r - 1)} + \frac{N\alpha}{3\varepsilon_0}$$

$$1 = \frac{N\alpha}{3\varepsilon_0} \left[ \frac{3}{\varepsilon_r - 1} + 1 \right]$$

$$\frac{N\alpha}{3\varepsilon_0} = \frac{1}{\left[ \frac{3}{\varepsilon_r - 1} + 1 \right]}$$

$$\frac{N\alpha}{3\varepsilon_0} = \frac{\varepsilon_r - 1}{\varepsilon_r + 2}$$

The above relation relating  $\alpha$  and  $\varepsilon_r$  is known as the 'Clausius - Moatti Equation.'

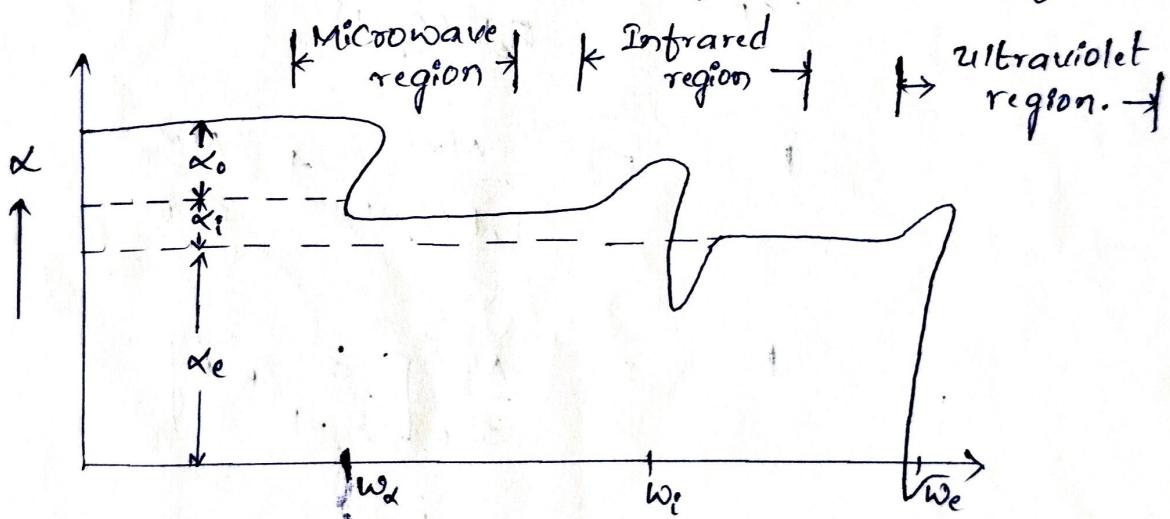
## Frequency Dependence of polarisability :-

consider a dielectric having electronic ( $\alpha_e$ ), ionic ( $\alpha_i$ ) and orientation ( $\alpha_o$ ) polarisabilities.

Then the total polarisability is the sum of all the above polarisabilities.

$$\text{i.e } \alpha = \alpha_e + \alpha_i + \alpha_o.$$

It is observed that the total polarisation varies with the frequency of applied alternating field. It has been found that the total polarisability of a dielectric substance shows marked differences in behaviour when studied as a function of frequency.



It is clear that as we go from the static to the optical region, the polarisability  $\alpha$  decreases by a substantial amount. Moreover the decrease in polarisability is not uniform - remarkable decrease occurs only in the microwave, infrared and ultraviolet regions.

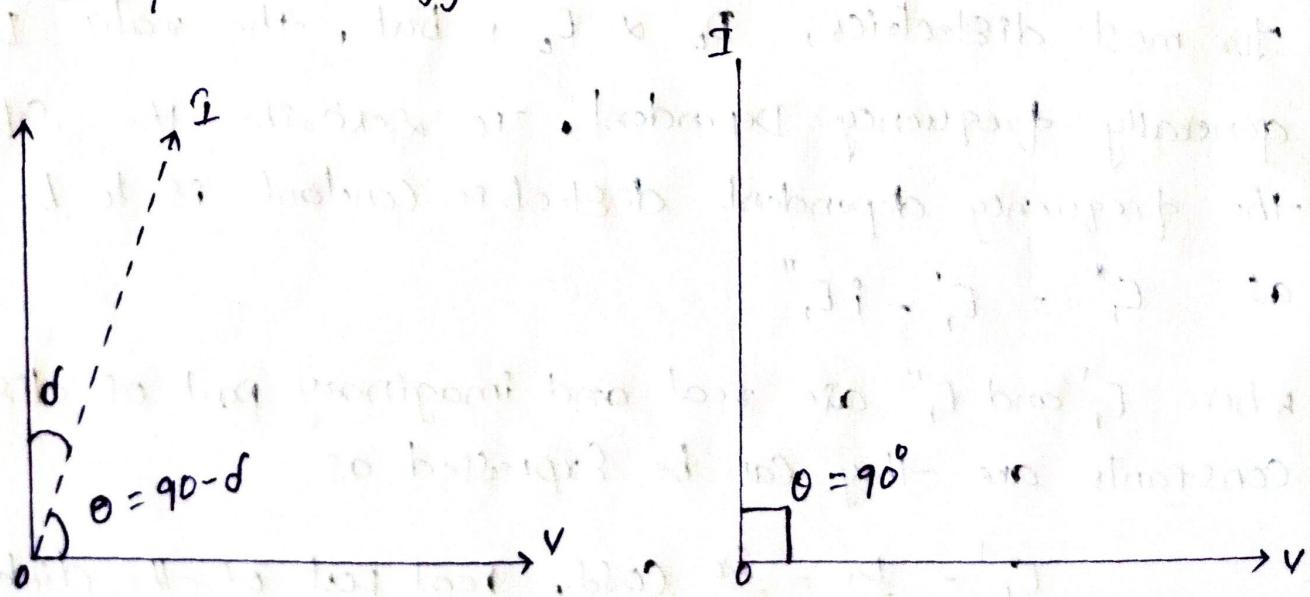
The orientation polarisability shows variation near microwave region similarly ionic and electronic polarisabilities show remarkable variations near infrared

and ultraviolet regions.

This behaviour of polarisability can be understood from the various polarisation processes and from the concept of relaxation time for each process. When the frequency of the applied field is much greater than the inverse of the relaxation time for a particular polarisation process, that particular polarisation process fails and so it does not contribute to polarisability. Thus the decrease of total polarisability with increase in frequency is due to the disappearance of  $\alpha_e$ ,  $\alpha_i$  &  $\alpha_e$  successively i.e. with increase in frequency, gradually the corresponding polarisabilities are not able to follow the frequency variations and disappear gradually.

### Dielectric loss :-

When a dielectric is subjected to the a.c. voltage, some of the electrical energy is absorbed by the dielectric material and later it is dissipated in the form of heat. This dissipated energy is called dielectric loss.



Angle b/w I and V for the case of ideal and lossy dielectrics.

In case of perfect insulator or ideal dielectric, there will not be any absorption of Energy, hence the phase angle between voltage and current is  $90^\circ$  as shown in fig.

In case of lossy or commercial dielectrics, the phase angle between the current and the voltage is less than  $90^\circ$ . i.e.  $90^\circ - \delta$ . Here, the angle  $\delta$  is known as dielectric loss angle which is measure of the power dissipated in each cycle & dielectric loss.

Suppose the dielectric is subjected to an alternating electric field,  $E = E_0 \cos \omega t$ , the polarization,  $p$  also varies periodically with time and so does the displacement vector  $D$ . However,  $p$  and  $D$  may lag behind in phase relative to  $E$ . Therefore,

$$D = D_0 \cos(\omega t - \delta)$$

$$\text{or } D = D_0 \cos \omega t \cos \delta + D_0 \sin \omega t \sin \delta.$$

$$\text{or } D = D_1 \cos \omega t + D_2 \sin \omega t$$

$$\text{where } D_1 = D_0 \cos \delta \text{ and } D_2 = D_0 \sin \delta$$

For most dielectrics,  $D_0 \propto E_0$ , but, the ratio  $D_0/E_0$  is generally frequency dependent. To describe the situation, the frequency dependent dielectric constant is to be introduced as  $E_r^* = E_r' - i E_r''$

where  $E_r'$  and  $E_r''$  are real and imaginary part of dielectric constants are they can be expressed as

$$E_r' = \frac{D_1}{E_0} = \frac{D_0}{E_0} \cos \delta, \text{ real part of the dielectric constant.}$$

$$E_r'' = \frac{D^2}{E_0} = \frac{D_0}{E_0} \sin \delta, \text{ imaginary part of the dielectric constant}$$

and  $E_r' = \tan \delta$ , dielectric loss tangent.

$E_r'$

Because, both  $E_r'$  and  $E_r''$  are frequency dependent, the phase angle  $\delta$  is also frequency dependent.

- \* If the dielectric Constant is real one, there will be no dielectric loss.
- \* The dielectric loss is increased by high voltage, high frequency and high temperature.
- \* The imaginary part of dielectric Constant represents dielectric loss.

## Magnetic Materials

①

(1) Magnet :- An iron ore which attracts small pieces of iron, cobalt, nickel etc is known as magnet.

(2) Magnetism :- The attracting property exhibited by the magnet is known as Magnetism.

(3) Magnetic Dipole :- A magnet consists of north and south poles. Any two opposite poles are separated by a finite distance constitute magnetic dipole.

(4) Magnetic Dipole moment :- (or) Magnetic moment :-

If 'm' is the magnetic pole strength and '2l' is the length of the magnet then, its magnetic dipole moment.

Magnetic moment is  $m \times 2l$

$$M_m = m \times 2l$$

when an electric current of 1 amp flows through a circular wire of one turn having an area of cross section 'A', then

$$M_m = I A$$

Magnetic field :- The space surrounding the magnet upto which its attracting influence is felt.

Magnetic field strength (H) :-

The force experienced by a unit north pole placed at a given point in a magnetic field is known as magnetic field strength. It is expressed in  $A/m$ .

(5) Magnetisation :-

The magnetic moment per unit volume is called magnetisation. It is expressed as  $A/m$ .  $M = M_m/V$ .

(4) Magnetic Susceptibility :- It is the ratio of the magnetisation produced in a sample to the magnetic field strength.  
 $\chi = \frac{M}{H}$ , It has no units.

Magnetic lines of force :-

The path in which a free unit north pole would move in a magnetic field is known as magnetic lines of force.

(5) Magnetic permeability :- (μ)

It is the ratio of the magnetic flux density (B) to the applied magnetic field strength (H).

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

Magnetic permeability of free space ( $\mu_0$ ) :-

It is the ratio of the magnetic induction field strength  $B_0$  of a free space to applied magnetic field (H).

$$\mu_0 = \frac{B_0}{H}$$

$$B_0 = \mu_0 H, \mu_0 = 4\pi \times 10^{-7} \text{ Tm}^{-1}$$

Relative magnetic permeability :- ( $\mu_r$ ) :-

It is the ratio of permeability of a material to the permeability of free space.

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

$$\mu = \mu_r \mu_0$$

Magnetic flux density :- It is defined as the number of magnetic lines of force passing through unit area.

$$\text{i.e. } B = \text{magnetic flux/area} = \phi/A$$

Units :-  $\text{wb/m}^2$  (or) tesla.

## Origin of Magnetic moment:-

on atoms the permanent magnetic moment can arise due to the following.

- (1) The orbital magnetic moment of the electrons.
- (2) The spin magnetic moment of the electrons and
- (3) Magnetic moment due to nuclear spin.

## \* Orbital Magnetic moment of electrons:-

We know that in an atom electrons revolve around the nucleus in different circular orbits.

Let 'm' be the mass of the electron and 'r' be radius of the orbit in which it moves with angular velocity  $\omega$ . Then the frequency of the revolving electron

$$(f) = \frac{\omega}{2\pi}$$

$$\text{Time period of revolutions} = \frac{2\pi}{\omega}$$

The revolving Electron in Circular orbit Establishes a Current

$$I = \frac{\text{charge}}{\text{time period}} = \frac{e \cdot \omega}{2\pi}$$

We know that the Current flowing through a Circular coil produces a magnetic field in a direction perpendicular to the area of the coil and it is identical to a magnetic dipole. The magnitude of the magnetic moment produced by a dipole is  $M_m = IA$

$$= - \frac{e\omega}{2\pi} (\pi r^2)$$

$$\text{Morbital} = \mu_m = -\frac{e\omega r^2}{2}$$

The angular momentum of the revolving electron is given by

$$\text{Angular momentum} = \text{Lineal momentum} \times \text{radius}$$

$$= q \times mv$$

$$= mvr$$

$$= m(r\omega)r$$

$$= mr^2\omega$$

$$\text{Morbital} = -\frac{e\omega r^2 \times m}{2 \times m}$$

$$= \left(-\frac{e}{2m}\right) mr^2\omega$$

$$= \left(-\frac{e}{2m}\right) \text{angular momentum}$$

$$\text{Morbital} = \left(-\frac{e}{2m}\right) L$$

The -ve sign indicates that the magnetic moment is anti parallel to the angular momentum.

The orbital gyromagnetic ratio =

$$\gamma = \frac{\text{Magnetic moment}}{\text{orbital angular momentum}}$$

$$\gamma = \frac{e}{2m}$$

According to modern atomic theory, the angular momentum of an electron in the orbit is determined by the orbital quantum number 'l'

$M_{\text{orbital}} = -\left(\frac{e}{2m}\right) \cdot \text{orbital angular momentum.}$

$$M_{\text{orbital}} = -\left(\frac{e}{2m}\right)\left(\frac{lh}{2\pi}\right)$$

$$= -\frac{ehl}{4\pi m}$$

$$= -\mu_B l$$

where  $l = 1, 2, 3 \dots$

$$\mu_B = \frac{eh}{4\pi m} \text{ is Bohr magneton.}$$

$$\mu_B = 9.27 \times 10^{-24} \text{ Am}^2.$$

Spin magnetic moment of electron:

The spinning electron about its own axis establishes the magnetic field and get a magnetic moment known as spin magnetic moment which is given by.

$$\mu_{\text{spin}} = \left(\frac{e\hbar}{4\pi m}\right) \vec{s}.$$

$$\mu_{\text{spin}} = \left(\frac{e}{2m}\right)\left(\frac{\hbar}{2\pi}\right)$$

$$\text{here } \vec{s} = \frac{1}{2}$$

$$\mu_{\text{spin}} = \frac{eb}{8\pi m} = 9.4 \times 10^{-24} \text{ Am}^2.$$

Magnetic moment due to nuclear spin:-

The atomic nucleus possess intrinsic spin and hence a magnetic moment is associated with this.

The magnetic moment of nucleus is

$$\mu_B = \frac{eb}{4\pi m_p} = 5.05 \times 10^{-27} \text{ Am}^2$$

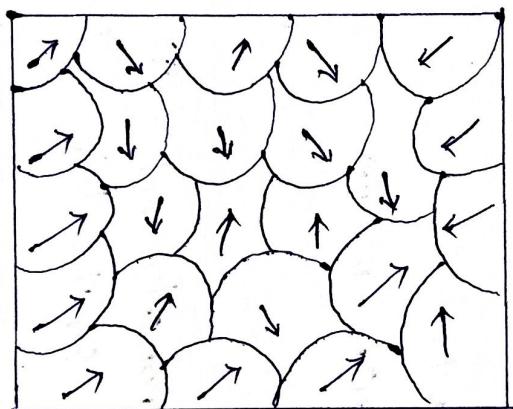
classification of magnetic materials:

Diamagnetic material	Ferromagnetic material	Paramagnetic material	Antiferromagnetic material	Heavi magnetic material
1) Net magnetic moment is zero	1) Large net magnetic moment exists in the direction opposite to the direction of applied magnetic field.	1) Large net magnetic moment exists in the direction of applied magnetic field.	1) Net magnetic moment exists in the direction opposite to the direction of applied magnetic field.	1) Net magnetic moment exists in the direction of applied magnetic field.
2) There is an induced magnetism opposite to the applied field.	2) There is a strong magnetism in the direction of the field.	2) There is an induced magnetism in the direction of the field.	2) There is an induced magnetism in the direction of the field.	2) There is a large magnetism in the direction of the field.
3) It repels the magnetic field.	3) It allows large number of magnetic lines of force to pass through it.	3) It allows large number of magnetic lines of force to pass through it.	3) It allows large number of magnetic lines of force to pass through it.	3) It allows large number of magnetic lines of force to pass through it.
4) Relative permeability is less than one i.e. $\mu_r < 1$	4) Relative permeability is greater than one i.e. $\mu_r > 1$	4) Relative permeability $\mu_r > 1$	4) $\mu_r > 1$	4) $\mu_r > 1$
5) Since the induced magnetic moment is opposite to the direction of applied field, the intensity of magnetisation 'M' is positive and the intensity of magnetisation of the applied field is negative.	5) Since the induced magnetic moment is in the direction of applied field, the direction of magnetisation 'M' is positive and the intensity of magnetisation 'M' is high.	5) Intensity of magnetisation 'M' is positive and moderate.	5) Intensity of magnetisation 'M' is positive and high.	5) Intensity of magnetisation 'M' is positive and high.

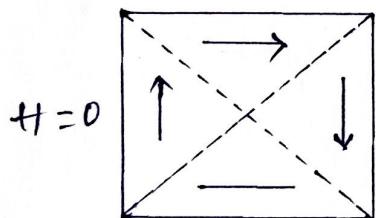
Magnetisation $M$ is positive and moderate and high negative.	6) $\chi$ is high and positive.	6) $\chi$ is low and positive.	6) $\chi$ is high and positive.
(e) Susceptibility $\chi$ is negative.	6) $\chi$ is low and positive.	6) $\chi$ is high and positive.	6) $\chi$ is high and positive.
7) Susceptibility $\chi$ is independent of temperature.	7) Susceptibility is dependent on temperature by the relation which is Curie - Weiss	7) $\chi = \frac{C}{T + T_c}$	7) $\chi = \frac{C}{T + T_c}$
	$\chi = \frac{C}{T}$		
	which is Curie Law		
			8) Scatts of transition elements
			8) - transition and rare Earth metals
			8) Ferrotes.
			8) Eg:- organic materials.

## Domain theory of ferromagnetism :-

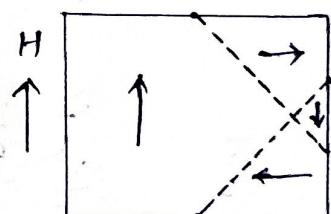
According to Weiss, a virgin specimen of ferromagnetic material consists of a no region or domains ( $\approx 10^{-6}$  m or larger) which are spontaneously magnetized. In each domain spontaneous magnetization varies from domain to domain. The resultant magnetization may hence be zero or nearly zero. When an external field is applied there are two possible ways of alignment for a random domain.



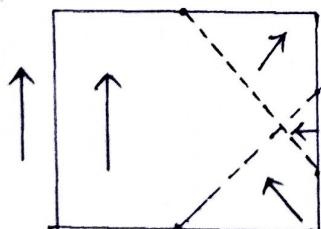
Random orientation  
of Magnetic moments  
of the Domains.



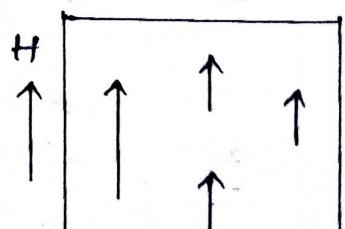
Domain orientation in the  
absence of magnetic field  
(a)



Domain enlargement / shrinkage  
due to weak fields  
(b)



Domain rotation due to  
Strong fields  
(c)



Saturation due to very  
high fields.  
(d)

(i) By motion of domain walls :-

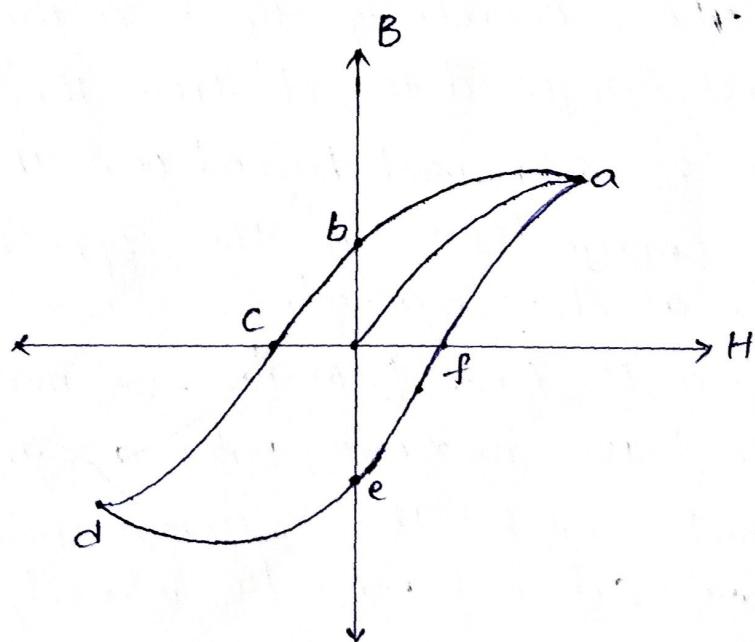
The volume of the domains that are favourably oriented with respect to the magnetizing field increases at the cost of those that are unfavourably oriented.

(ii) By rotation of domains :-

when the applied magnetic field is strong, rotation of the direction of magnetization occurs in the direction of the field.

Hysteresis :-

when a specimen of ferromagnetic material is placed in a magnetic field. The specimen is magnetised by induction. As the magnetic intensity ( $H$ ) is varied the flux density ( $B$ ) in the material does not vary linearly with ' $H$ '. The variation in ' $B$ ' with variation in ' $H$ ' is called B-H Curve.



The point 'o' represents an initially un magnetised Specimen and a zero magnetic intensity. As  $H$  is increased,  $B$  also increases, but not uniformly and a point such as 'd' is reached.

If ' $H$ ' is now decreased ' $B$ ' also decreases but following a path "ab". Thus ' $B$ ' lags behind when  $H$  becomes zero.  $B$  still has a value equal to "ob". This magnetic flux density remaining in the Specimen in the absence of any External field is called the residual magnetism. The power of retaining this magnetism is called the retentivity.

If the magnetic intensity ' $H$ ' is now increased in the reverse direction, the value of  $B$  further decreases, still lagging behind  $H$ , and becomes zero when ' $H$ ' has a value equal to "oc". This value of the magnetic intensity is called the coercivity of the Specimen. Thus, coercivity  $H_c$  is a measure of the magnetic intensity required to destroy the residual magnetism.

As  $H$  is increased beyond  $oc$ , the Specimen is increasingly magnetised in the opposite direction and a point such as d is reached.

By taking  $H$  back from its -ve maximum through zero, to its original +ve maximum value a similar defa is obtained at points b and e where the Specimen is magnetised in the absence of any external magnetic intensity, it is called a "permanent magnet".

The closed curve abcdefa which represents a cycle of magnetisation of the Specimen is known as "Hysteresis".

## Hard and soft magnetic materials :-

### Hard magnetic materials

- (1) Hard magnetic materials have large hysteresis loop area and hysteresis loss is large.
- (2) The coercivity and retentivity are large.
- (3) Magnetisation and demagnetisation of these materials is very difficult.
- (4) They require high magnetic field for magnetisation and demagnetisation.
- (5) Magnetic susceptibility is large. Very small.
- (6) Magnetic permeability is very small.
- (7) Due to broader loop these are used to make permanent magnets.
- (8) Ex:-

- (1) Iron-Silicon alloys
- (2) Nickel-Iron alloys
- (3) Iron-Cobalt alloys

### Applications:

- (1) used in dc meters

### Soft magnetic materials

- (1) Soft magnetic materials have low hysteresis loop area and hysteresis loss is small.
- (2) The coercivity and retentivity are small.
- (3) These are easily magnetised and demagnetised.
- (4) They require low magnetic field for magnetisation and demagnetisation.
- (5) Magnetic susceptibility is very small. Large.
- (6) Magnetic permeability is large.
- (7) These are used to make electromagnets.
- (8) Ex:-

- (1) Carbon steels
- (2) Tungsten steels
- (3) Chromium steels

### Applications

- (1) used in Electrical

and measuring devices

(2) used in speedometers and  
sensors in automobiles motors.

Equipments-

(3) used in transform motors,  
relays and sensors.

(3) used in microwave isolators.