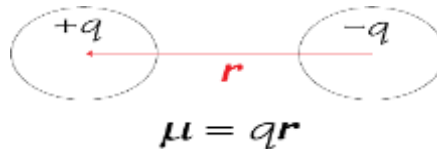


UNIT- III DIELECTRIC & MAGNETIC MATERIALS

Fundamental Definitions

Electric dipole: Two opposite charges of equal in magnitude and separated by a finite distance constitute an electric dipole.



Dipole moment: It is the product of one of the charges and the distance between the two charges.

$$\mu = q r$$

It is a vector quantity. The direction of μ is from negative to positive.

Dielectric constant (ϵ_r): Dielectric constant is the ratio between the permittivity of the medium to the permittivity of the free space.

$$\epsilon_r = \frac{\epsilon}{\epsilon_0}$$

Since it is the ratio of same quantity, has no unit.

Polarization (or) Electric Polarisation : The process of producing electric dipoles which are oriented along the field direction is called polarization in dielectrics.

Polarization vector (P): The dipole moment per unit volume of the dielectric material is called polarization vector P.

If μ is the average dipole moment per molecule and N is the number of molecules per unit volume, then polarization vector,

$$P = N\mu = N\alpha E$$

Polarizability(α): The ability of a dielectric to allow its charges to get separated in the presence of an electric field is known as polarisability.

$$\alpha = \frac{\mu}{E} \quad \text{Fm}^2$$

Dielectric Susceptibility (χ) : It measures the amount of polarization in a given electric field produced in a dielectric.

$$\chi = \frac{P}{E\epsilon_0}$$

It has no units.

Electric displacement or Electric flux density (D) : Consider a polarised dielectric in resultant electric field E. The field is characterised by electric lines of forces. These lines of forces while passing through the dielectric make it polarized. The total number of electric lines of force passing through the dielectric is known as electric flux density

$$D = \epsilon_0 E + P$$

Relation between electric susceptibility(χ) and dielectric constant (ϵ_r)

We know that

$$D = \epsilon_0 E + P \quad \text{..... (1)}$$

$$D = \epsilon E \quad \text{..... (2)}$$

From eq's (1) & (2)

$$\epsilon E = \epsilon_0 E + P$$

$$\epsilon_r \epsilon_0 E = \epsilon_0 E + P \quad (\epsilon = \epsilon_r \epsilon_0)$$

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

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

$$(\epsilon_r - 1) = \chi$$

Types of Polarizations:

Polarization occurs due to several atomic mechanisms. When the specimen is placed inside electric field, mainly four types of polarizations are possible. Those are

1. Electronic polarization
2. Ionic polarization
3. Orientation or Dipolar polarization
4. Space charge polarization

Electronic polarization:

Electronic polarization occurs due to the displacement negative electron cloud of each atom with respect to its nucleus in the presence of electric field. When an external field is applied and there by creates a dipole moment in the dielectric.

Therefore induced dipole moment $\mu = \alpha_e E$

Where is α_e the electronic polarizability.

- Electronic polarizability is occurs in al dielectrics for any state of aggregation.
- Tthe electronic polarisation sets in a over a period of time, of the order of 10^{-14} to 10^{-15} sec.
- Polarizability is independent of temperature.

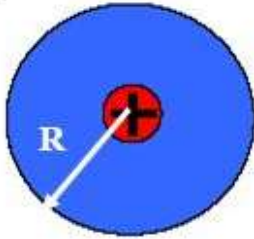
Calculation of electronic polarizability:**(I) Without Electric field:**

Let us consider a classical model of an atom. Assume the charge of the nucleus is (+ Ze)and the nucleus is surrounded by an electron cloud of charge (– Ze) which is distributed in sphere of radius R.

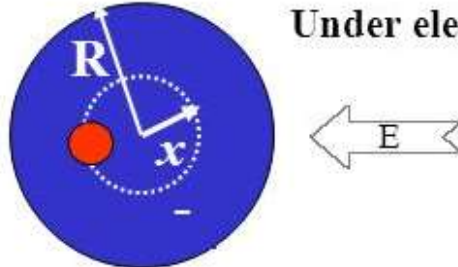
The charge density of the charged sphere = $\frac{-Ze}{\frac{4}{3}\pi R^3}$

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

No field



Under electric field



(II) With Electric field:

When the dielectric is placed in an electric field E, two phenomena occurs

- ❖ Lorentz force due to the electric field tends to separate the nucleus and the electron cloud from their equilibrium position.
- ❖ After the separation, an attractive coulomb force arises between the nucleus and electron cloud which tries to maintain the original equilibrium position.
- ❖ Let x be the displacement made by the electron cloud from the positive core .Since the nucleus is heavy it will not move when compared to the movement of electron cloud here , $x \ll R$, where R is the radius of the atom.
- ❖ Since the Lorentz and coulombs forces are equal and opposite in nature, equilibrium is reached.

At equilibrium state , Lorentz force = Coulomb force

$$\text{Lorentz force} = \text{charge} \times \text{field} = -ZeE \text{ -----(2)}$$

$$\text{Coulomb Force} = \frac{\text{charge} \times (\text{total negative charges}(Q) \text{ enclosed in the sphere of radius } x)}{4\pi\epsilon_0 x^2} \text{ --- (3)}$$

Here the total number of negative charges (Q) encloses in the sphere of radius x is

$$= \frac{4}{3}\pi x^3 \times \rho = \frac{4}{3}\pi x^3 \times \frac{-3Ze}{4\pi R^3}$$

$$\text{Coulomb force} = +Ze \times \frac{\left(\frac{-zex^3}{R^3}\right)}{4\pi\epsilon_0 x^2} = \frac{-Z^2 e^2 x}{4\pi\epsilon_0 R^3} \text{ ----- (4)}$$

At equilibrium state

$$\text{Lorentz force} = \text{Coulomb force}$$

From eq's(2) & (4)

$$-ZeE = \frac{-Z^2 e^2 x}{4\pi\epsilon_0 R^3} \text{-----(5)}$$

$$x = \frac{4\pi\epsilon_0 R^3 E}{Ze} \text{----- (6)}$$

Therefore the displacement of electron cloud(x) is proportional to the applied electric field E.

Dipole moment:

Now the two electric charges +Ze and -Ze are displaced by a distance under the influence of the field and form a dipole.

Induced dipole moment = magnitude of charge × displacement

$$\mu = ZeX \text{-----(7)}$$

From eq's (6) & (7)

$$\mu = Ze \times \frac{4\pi\epsilon_0 R^3 E}{Ze}$$

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

$$\mu = \alpha_e E \text{--- -- (8)}$$

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

where

α_e is called electronic polarizability
and polarisation

$$P_e = N \mu = N \alpha_e E$$

Ionic polarization:

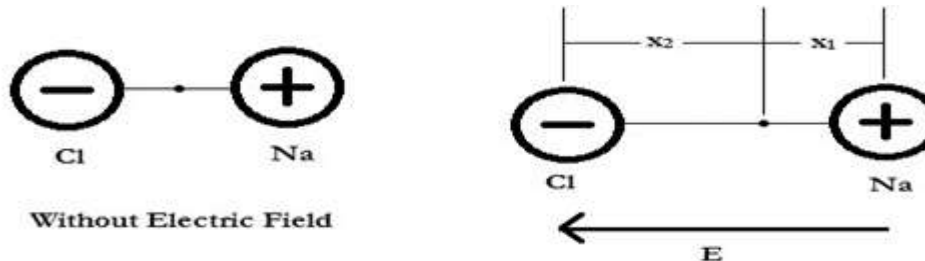
- ❖ This is due to the displacement of cations and anions in opposite directions and occurs in an ionic solid. This type of polarization occurs in ionic dielectrics like NaCl.
- ❖ When such a dielectric material is subjected to an external electric field, adjacent ions of opposite sign undergoes displacement and this displacement results either increase or decrease in the distance of separation between ions.
- ❖ If x_1 and x_2 are the displacements of positive and negative ions in an ionic crystal due to the application of electric field E, then dipole moment is

$$\mu = e(x_1 + x_2) \text{----- (1)}$$

❖ Dipole moment is

$$\mu = \alpha_i E$$

❖ Suppose an electric field is applied in the +ve x direction, the +ve ions move to the right by x_1 and the -ve ions move to the left by x_2 .



❖ Due to the electric field, the Lorentz force on each ion is

$$F = eE$$

❖ For Na^+ ion

The Lorentz force is $F_1 = eE$ (2)

Restoring force is $F_2 = \beta_1 x_1$ (3)

❖ Similarly for Cl^-

The Lorentz force is $F_3 = eE$ (4)

Restoring force is $F_4 = \beta_2 x_2$ (5)

Where β_1 and β_2 are restoring force constants of cation and anion.

❖ Restoring force constants depend upon the mass of the ion and angular frequency of the molecule in which ions are present. M is the mass of the positive and m is the mass of negative ions respectively.

$$\beta_1 = m\omega_0^2$$

$$\beta_2 = M\omega_0^2$$

At equilibrium state, the Lorentz and restoring forces are equal.

For Na^+

$$F_1 = F_2$$

$$eE = \beta_1 x_1$$

$$eE = M\omega_0^2 x_1$$

$$x_1 = eE / M \omega_0^2 \quad \text{..... (6)}$$

For Cl^-

$$x_2 = eE/m\omega_0^2 \quad \dots\dots\dots (7)$$

$$(x_1 + x_2) = \frac{eE}{\omega_0^2} \left(\frac{1}{M} + \frac{1}{m} \right)$$

Dipole moment is

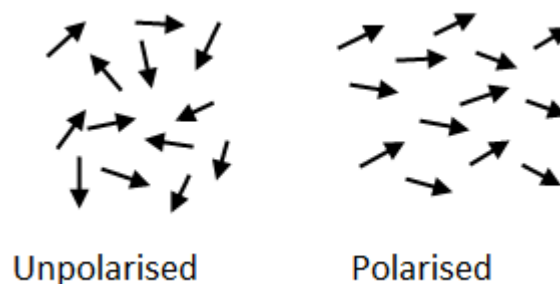
$$\begin{aligned} \mu &= e(x_1 + x_2) \\ &= \frac{e^2 E}{\omega_0^2} \left(\frac{1}{M} + \frac{1}{m} \right) \\ \alpha_i = \mu/E &= \frac{e^2}{\omega_0^2} \left(\frac{1}{M} + \frac{1}{m} \right) \end{aligned}$$

$$P_i = N \mu = N \alpha_i E$$

Thus the ionic polarizability (α_i) is inversely proportional to square of the natural frequency of the ionic molecule and is reduced mass is equal to $\left(\frac{1}{M} + \frac{1}{m} \right)$

Orientational or Dipolar polarization:

- This type of polarization occurs in polar dielectrics.
- Without the external field the molecules are oriented at random. So the net dipole moment is zero.
- When external field is applied, the polar molecules orient favourably into the field direction.



- The polarization due to such alignment is called orientation polarisation.
 - Orientation polarisation dependent on temperature. With increase of temperature, the thermal energy tends to randomize the alignment.
 - Hence the orientational polarizability is strongly dependent on temperature.
- Therefore the orientational polarizability is

$$\alpha_o = \frac{\mu^2}{3KT}$$

$$P_o = N\alpha_o E$$

Space charge polarization:

- This occurs in heterogeneous dielectric materials and also in homogeneous dielectric having impurities, pores filled with air etc.
- Mainly hydrogen and lithium ions caused this polarization in ceramics and glasses.
- It takes relatively longer time compare to other types of polarizations.

Total polarization and polarizability:

The total polarizability of a gas can be written as

$$\alpha_T = \alpha_e + \alpha_i + \alpha_o + \alpha_s$$

Since the space charge polarizability is very small when compared to the other types of polarizabilities,

$$\alpha_T = \alpha_e + \alpha_i + \alpha_o$$

$$\alpha_T = 4\pi\epsilon_0 R^3 E + \frac{e^2}{\omega_0^2} \left(\frac{1}{m} + \frac{1}{M} \right) + \frac{\mu^2}{3KT}$$

The total polarization of a material is the sum of the contribution from the various sources above

$$P_T = P_e + P_i + P_o + P_s$$

$$P_T = NE \left\{ 4\pi\epsilon_0 R^3 E + \frac{e^2}{\omega_0^2} \left(\frac{1}{m} + \frac{1}{M} \right) + \frac{\mu^2}{3KT} \right\}$$

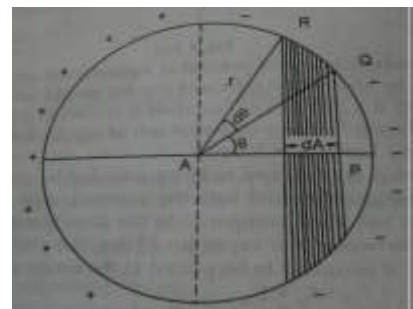
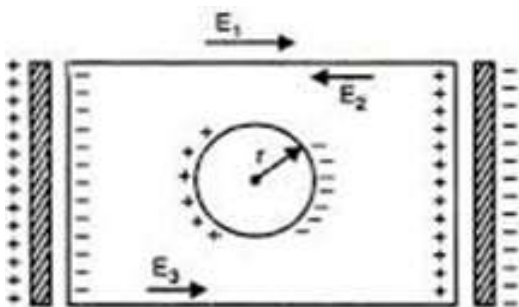
This equation is known as **Langevin -Debye** equation.

Local field or internal field in dielectrics

When an external electric field is applied across a dielectric, the intensity of electric field felt by a given atom is not equal to the applied electric field .

- The internal field (**E_i**) is defined as the electric field acting on the atom is equal to the sum of the electric fields created by the neighbouring polarized atoms and the applied field. This field is responsible for polarizing the atom.
- The internal field is also called Lorentz field.

LORENTZ METHOD TO FIND INTERNAL FIELD:



- A dielectric material is placed in an external electric field (E_1), i.e It is placed in between two plates of a parallel plate capacitor.
- Consider an imaginary sphere inside the solid dielectric of radius 'r'. Radius of the sphere is greater than the radius of the atom.
- Thus there are many atomic dipoles within the sphere. Electric field at the centre of the sphere is called internal field which is made up of the following four factors.

$$E_i = E_1 + E_2 + E_3 + E_4 \quad \text{----- (1)}$$

E_1 = Electric field due to the charges on the capacitor plates (externally applied).

E_2 = Electric field due to polarized charges on the plane surface of the dielectric.

E_3 = Electric field due to polarized charges induced on the surface of the sphere.

E_4 = Electric field due to permanent dipoles of atoms inside the sphere.

To find E_1

E_1 is the field intensity at A due to the charge density on the plates.

To find E_2

E_2 is the field intensity at A due to the charge density induced on the two sides of the dielectric.

Since E_1 and E_2 are in opposite direction. The total electric field is

$$E = E_1 + E_2 \quad \text{----- (2)}$$

To find E_4

E_3 is the field intensity at O due to other atoms contained in the cavity. We are assuming a cubic structure, so

$$E_4 = 0 \quad \text{----- (3)}$$

Eq .s(2) & (3) in (1) ,it becomes

$$E_i = E + E_3 \quad \text{----- (4)}$$

To find E_3

E_3 is the field intensity due to charges on the surface of the cavity and was calculated by Lorentz method.

The enlarged view of the cavity as shown in fig. If ds is the surface area of the sphere of radius r lying between θ and $\theta + d\theta$, where θ is the direction with reference to the direction of the applied force,

$$ds = 2\pi(PQ)(QR)$$

But

$$\sin\theta = \frac{PQ}{r}, PQ = r \sin\theta$$

$$QR = r d\theta$$

Hence

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

The charge dq on the surface ds is equal to the normal component of polarization multiplied by the surface area.

$$dq = ds \times P \cos\theta = 2\pi r^2 \sin\theta d\theta \times P \cos\theta$$

The field due to this charge at A, denoted by dE_3 in the direction $\theta = 0$ is

$$dE_3 = \frac{dq \times 1 \times \cos\theta}{4\pi\epsilon_0 r^2}$$

$$= \frac{2\pi r^2 \sin\theta d\theta \times P \cos\theta \cos\theta}{4\pi\epsilon_0 r^2}$$

$$= \frac{P 2\pi r^2 \sin\theta \cos^2\theta d\theta}{4\pi\epsilon_0 r^2}$$

Thus the total field E_3 due to the charges on the surface of the entire cavity is obtained by integrating dE_3

$$\int_0^\pi dE_3 = \int_0^\pi \frac{P 2\pi r^2 \sin\theta \cos^2\theta d\theta}{4\pi\epsilon_0 r^2} = \frac{P}{2\epsilon_0} \int_0^\pi \sin\theta \cos^2\theta d\theta$$

$$= \frac{P}{2\epsilon_0} \int_0^\pi x^2 (-dx)$$

$$\cos\theta = x \text{ and } dx = -\sin\theta d\theta$$

$$= \frac{P}{2\epsilon_0} \int_0^\pi (\cos^2\theta)(-\cos\theta)$$

$$= -\frac{P}{2\epsilon_0} \left[\frac{\cos^3\theta}{3} \right]_0^\pi$$

$$= -\frac{P}{6\epsilon_0} [-1 - 1]$$

$$E_3 = \frac{P}{3\epsilon_0}$$

Therefore internal field in dielectrics is

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

Clausius –Mosotti relation:

Elemental solid dielectrics like Ge,Si,Diamond,etc., have no permanent dipoles or ions and will have only cubic structure,thereby exhibiting only electronic polarization.The total polarization is

$$P = N\alpha E_i$$

where E_i is local field in dielectrics

$$P = N\alpha \left[E + \frac{P}{3\epsilon_0} \right] \dots\dots\dots (1)$$

$$P = \epsilon_0 E(\epsilon_r - 1) \dots\dots\dots (2)$$

equating eqn.(1) &(2)

$$N\alpha \left[E + \frac{\epsilon_0 E(\epsilon_r - 1)}{3\epsilon_0} \right] = \epsilon_0 E(\epsilon_r - 1)$$

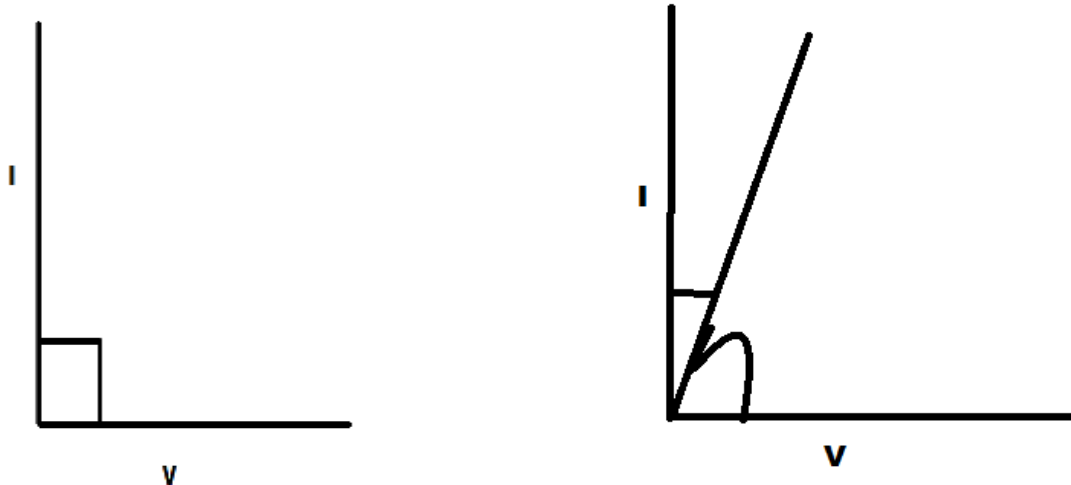
$$\frac{N\alpha E 3\epsilon_0}{3\epsilon_0} + N\alpha \left[\frac{\epsilon_0 E(\epsilon_r - 1)}{3\epsilon_0} \right] = \epsilon_0 E(\epsilon_r - 1)$$

$$\frac{N\alpha E \epsilon_0}{3\epsilon_0} [3 - (\epsilon_r - 1)] = \epsilon_0 E(\epsilon_r - 1)$$

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

Dielectric loss:

- When a dielectric is subjected to the a.c. voltage, the electrical energy is absorbed by the material and is dissipated in the form of heat. This dissipation of energy is called dielectric loss. Since this involves heat generation and heat dissipation, this assumes a dominating role in *high voltage applications*.
- In an ideal dielectric, the current leads the voltage by an angle of 90° is shown in fig. But in case of a commercial dielectric, the current does not exactly lead the voltage by 90° . It leads by some other angle δ is less than 90° . the angle $(90 - \delta)$ is known as the dielectric loss angle.
- The dielectric power loss is given by



Power loss in dielectrics is

$$P = VI \cos \theta$$

For a perfect dielectrics, $\theta = 0$, $P = 0$. It means no power loss.

For a commercial dielectrics, $\theta = (90 - \delta)$

$$P = VI \cos (90 - \delta)$$

$$= VI \sin \delta$$

$$= VI \tan \delta \quad (\sin \delta = \tan \delta) \quad \dots\dots\dots (1)$$

- According Ohm's law $V = IR$

$$I = \frac{V}{R} = \frac{V}{X_C} \quad (X_C = R = \text{capacitive reactance}) \quad \dots\dots\dots (2)$$

- From eqn.(1) and (2)

$$P = V \frac{V}{X_C} \tan \delta = \frac{V^2}{X_C} \tan \delta \quad \dots\dots\dots (3)$$

- But the frequency $f = \frac{1}{2\pi RC} = \frac{1}{2\pi X_C C}$

$$X_C = \frac{1}{2\pi fC} \dots\dots\dots (4)$$

Substitute eqn (4) in eqn(3),we get

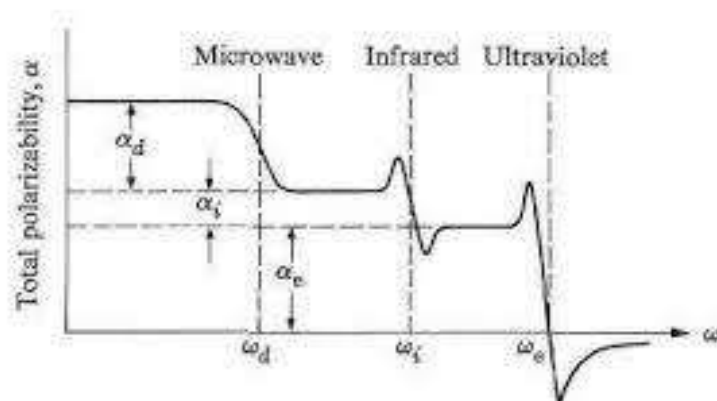
$$P = V^2 2\pi fC \tan \delta \dots\dots\dots (5)$$

Where $\tan \delta$ is power factor of the dielectric.

- The power loss depends on only on the power factor of the dielectric as long as the applied voltage, frequency and capacitance are kept constant.
- The dielectric loss is increased by the following factors:
 - High frequency of the applied voltage
 - High value of the applied voltage
 - High temperature
 - Humidity

FREQUENCY DEPENDENCE OF POLARIZABILITY

- On the application of alternating electric field the polarization process occur as a function of time.
- Electronic polarizability is extremely rapid and is complete at any instant of time even when the frequency of the voltage is very high in the optical ranges. Thus it occurs at all frequencies.
- Ionic polarizability is slower and the ions do not respond at all when the voltage correspond to visible frequencies. So it does not occur at visible frequencies.
- Orientational polarization is slower than the ionic polarizability and occurs only at frequencies which are smaller than the infrared frequencies.
- Space charge polarization is slower process and occurs only at lower frequencies (50-60 Hz).
- The total polarizability is very high at low frequencies and very low at higher (optical) frequencies.



Complex dielectric constant:

It is a physical quantity that expresses the capability of materials to withstand external fields that have a strong dependence on the frequency.

When a dielectric is subjected to an alternating field the polarization vector (P) also varies periodically with time and so does the displacement vector D. In general, however, P and D may lag behind in phase relative to E so that for example if $E = E_0 \cos(\omega t - \delta)$, then the displacement vector,

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

$$D = D_0 \cos\delta \cos \omega t - D_0 \sin\delta \sin \omega t$$

$$D = D_1 \cos \omega t - D_2 \sin \omega t$$

Where δ is phase angle,

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

For most dielectrics D_0 is proportional to E_0 but the ratio $\left(\frac{D_0}{E_0}\right)$ is generally frequency dependent. To describe this, one may thus introduce two frequency dependent dielectric constants.

$$\epsilon'_r = \frac{D_1}{E_0} = \frac{D_0}{E_0} \cos\delta$$

$$\epsilon''_r = \frac{D_2}{E_0} = \frac{D_0}{E_0} \sin\delta$$

Where ϵ'_r and ϵ''_r are real and imaginary parts of the dielectric constants.

It is frequently convenient to sum these two constants into a large **complex dielectric constant**,

$$\epsilon_r^* = \epsilon'_r - i\epsilon''_r$$

$$\tan \delta = \frac{\epsilon''_r}{\epsilon'_r}$$

Properties:

1. Complex dielectric constant $\epsilon_r^* = \epsilon'_r - i\epsilon''_r$ Where ϵ'_r and ϵ''_r are real and imaginary parts of the dielectric constants and $i = \sqrt{-1}$
2. If the dielectric constant of a material is a real quantity then there will be no absorption of energy or dielectric loss.
3. The dielectric loss is also increased by high voltage, high frequency, high temperature and humidity.
4. The imaginary part of complex dielectric constant (ϵ''_r) gives rise to absorption of energy by the material from the alternating field, i.e., it represents the dielectric loss.

Applications of dielectrics:

Dielectrics are widely used as insulating materials.

Another very important application of dielectric materials is their use as energy storage capacitors. Depending on the application and type of dielectric used,the capacitor may be grouped into the following four categories.

1. **Capacitors with vacuum, air or inert gas as dielectrics:** In this type of capacitors dielectric loss are very less. The value of capacitance is not very large. Therefore there are used in radio frequency circuits and in low frequency measuring circuits.
2. **Capacitors with mineral oils as dielectrics:** In this type of capacitors dielectric loss are not very small. The value of the capacitance are very large. Hence these are used in high voltage applications.
3. **Capacitors with solid dielectrics:** Glass, mica etc., are used in these capacitors. These types of capacitors are used in laboratories as standard capacitors. They have high dielectric constant and high insulator resistance. The dielectric constant does not vary with temperature.
4. **Capacitors with both solid and liquid dielectrics:** In this type of capacitors, combination of solids such as papers, films of synthetic materials glass, mica etc and liquids such as mineral oil, castor oil silicon oil etc .are used. These capacitors provide high value of capacitance. These are very useful for power factor correction in electric power distribution.

MAGNETIC MATERIALS

Fundamental definitions

Magnetic flux(ϕ): The number of lines passing normally through an area. Its unit is Weber.

Magnetic induction (or) Magnetic flux density (B):

The magnetic induction in any material is the number of magnetic lines of force passing through a unit area of cross – section of magnetic material Its unit is Weber/ m^2 or Tesla.

$$B = \frac{\phi}{A} \quad \frac{wb}{m^2} \text{ or Tesla}$$

Magnetic field intensity (or) strength (H): Magnetic field intensity at any point in the magnetic field is the force experienced by a unit North Pole placed at that point. Its unit is (A/)

Magnetization (or) Intensity of magnetization (M): It is defined as the magnetic moment per unit volume. Its units is (A/)

Magnetic susceptibility (χ): The ratio of intensity of magnetization (M) produced to the magnetic field strength (H) in which the material is placed.

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

$$M \propto H$$

$$M = \chi_m H$$

$$\text{magnetic susceptibility } \chi_m = \frac{M}{H}$$

Magnetic permeability of medium (μ): It is defined as the ratio of magnetic induction B in a substance to the applied magnetic field intensity.

$$B \propto H$$

$$B = \mu H$$

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

Relative permeability (μ_r) :

The ratio of permeability of medium to the permeability of free space (μ_0) is called relative permeability μ_r of the solid.

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

$$\mu_r = \frac{\frac{B}{H}}{\frac{B_0}{H}} = \frac{B}{B_0}$$

Relation between magnetic permeability, relative permeability and Susceptibility :

$$B \propto H$$

$$B = \mu H$$

$$B = \mu_0 \mu_r H$$

$$B = \mu_0 \mu_r H + \mu_0 H - \mu_0 H$$

$$B = \mu_0 H + \mu_0 H (\mu_r - 1)$$

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

Where M is the magnetization

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

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

$$\text{relative permeability } \mu_r = \frac{\mu}{\mu_0} \rightarrow \frac{B/H}{B/(H + M)}$$

$$\mu_r = \frac{H + M}{H}$$

$$\mu_r = 1 + \frac{M}{H}$$

$$\mu_r = 1 + \chi_m$$

Magnetic moment:

- Materials made up of atoms. These atoms consist of a nucleus surrounding which electrons are revolving in their orbits. This orbital motion of electron establishes a magnetic field and hence we get a magnetic moment of the electrons.
- When an electric current I ampere flows through a circular loop produced by the revolving of electrons having an area of cross section A square metre.

$$\mu_m = I A \quad \text{Am}^2$$

- When the electrons revolves around the nucleus Orbital magnetic moment arises, similarly when the electron spins, spin Magnetic moment arises.
- The permanent Magnetic Moments can arise due to the
 - 1.The orbital magnetic moment of the electrons
 - 2.The spin magnetic moment of the electrons, and
 - 3.The spin magnetic moment of the nucleus.

Origin of Magnetic moment:

Magnetic moment arises in an element due to the presence of angular momentum. There are three different types, namely

1. Orbital angular momentum
2. Spin angular momentum
3. Nuclear spin angular momentum

Orbital angular momentum: When the electrons revolves around the nucleus Orbital magnetic moment arises, similarly when the electron spins, spin Magnetic moment arises.

Consider an atom & each electron in that, orbiting around the nucleus produces a loop current

$$i = q / t$$

$$i = q f$$

Where f is a frequency of electron..

If L is the angular momentum of electron, the Magnetic moment of the electron

$$\mu_{lm} = (\text{Area of loop}) \times (\text{Current})$$

$$\mu_{lm} = (\pi r^2) \left(\frac{q}{2\pi} \times \omega \right)$$

$$\mu_{lm} = \frac{q}{2m} \cdot mvr$$

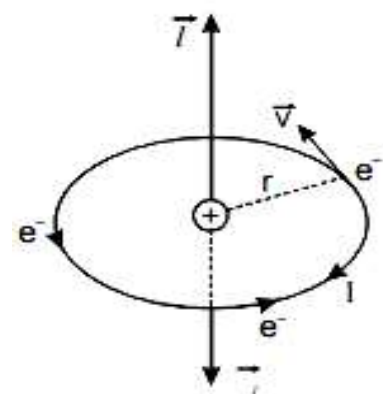
$$\mu_{lm} = \frac{q}{2m} \cdot L$$

Where L is a Angular Momentum of electron

$$L = mvr = \frac{lh}{2\pi}$$

$$\mu_{lm} = \frac{qh}{4\pi m} \cdot \sqrt{l(l+1)}$$

$$\mu_{lm} = \mu_B \cdot \sqrt{l(l+1)}$$



where, μ_B (Bhor, magnaton) $= \frac{qh}{4\pi m} \rightarrow 9.27408 \times 10^{-24} \text{ A-m}^2$

Spin angular momentum:

Besides the orbital motion of an electron, It rotates about its own axis. Magnetic moment associated with spinning of the electron is called spin magnetic moment. Spin angular momentum is expressed as

$$\mu_s = \frac{qh}{4\pi m} = 9.4 \times 10^{-24} \text{ A-m}^2$$

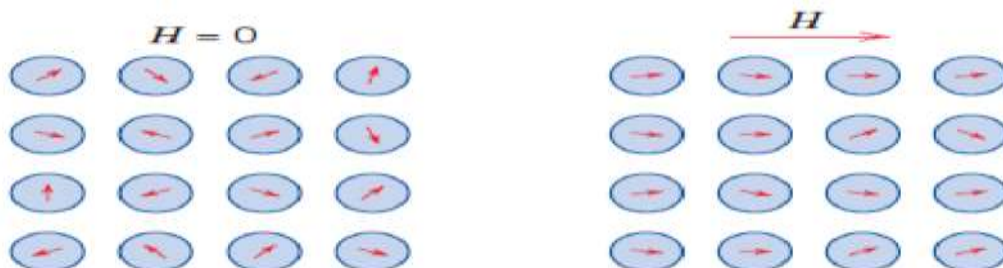
Nuclear spin angular momentum: The atomic nucleus possesses intrinsic spin(called nuclear spin) and hence a magnetic moment is associated with this. As the electron magnetic moment is expressed in the unit of Bohr magneton, the nuclear magnetic moment is expressed in the unit of nuclear magneton

$$\mu_n = \frac{qh}{4\pi M_P} = 5.05 \times 10^{-29} \text{ A-m}^2$$

Classification of magnetic materials:

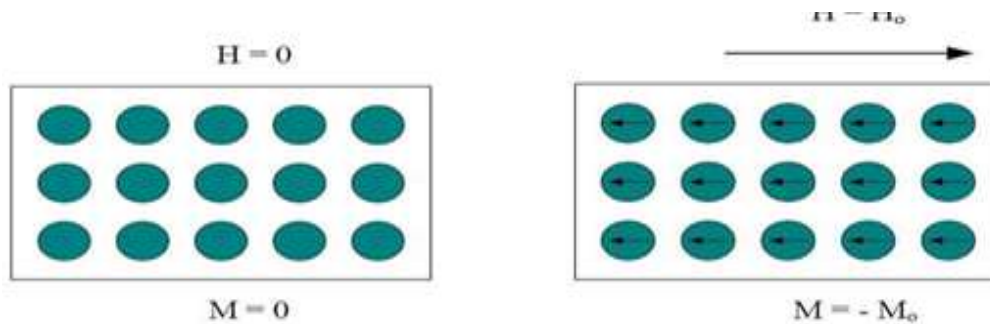
Paramagnetic materials

- Paramagnetic materials get magnetized in the direction of the magnetic field.
- Weak attraction is characteristic property of Para magnetism.
- Paramagnetic material has magnetic dipoles.
- Relative permeability is greater than one but small i.e. this indicate that when paramagnetic substance is placed in a uniform magnetic field, the field inside the material will be more than the applied field.
- The magnetic susceptibility is small and positive.
- The magnetic susceptibility of paramagnetic is inversely proportional to absolute temperature i.e. $\chi = \frac{c}{T}$. This is called curie law, c is called Curie constant.
- Spin alignment is random .



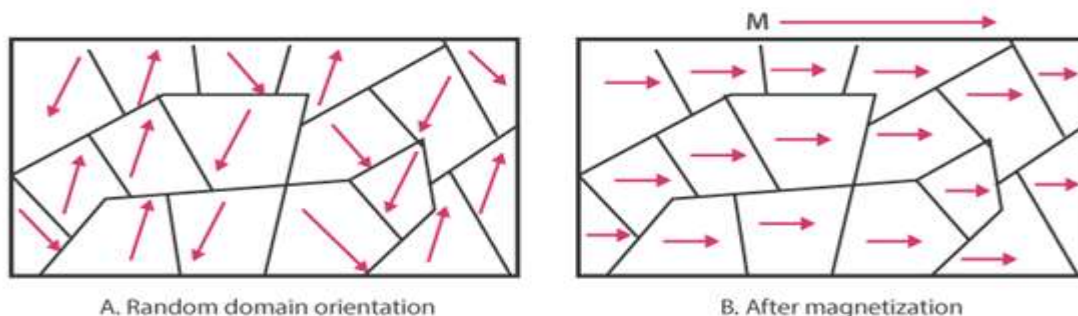
Diamagnetic materials

- Diamagnetic material gets magnetized in a direction opposite to the magnetic field.
- Weak repulsion is the characteristic property of diamagnetism.
- Permanent dipoles are absent.
- Relative permeability is less than one but positive.
- The magnetic susceptibility is negative and small. It is not affected by temperature.
- Diamagnetism is universal i.e. all materials when exposed to external magnetic fields, tend to develop magnetic moments opposite in the direction to the applied field.
- When placed inside a magnetic field, magnetic lines of force are repelled.



Ferromagnetic materials:

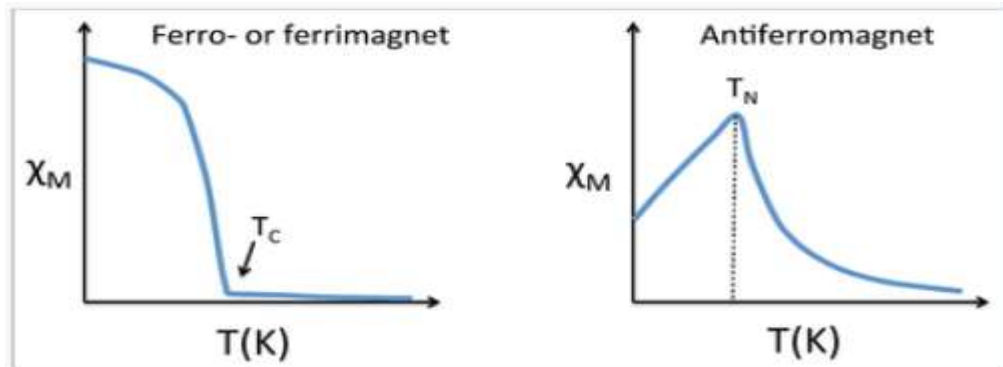
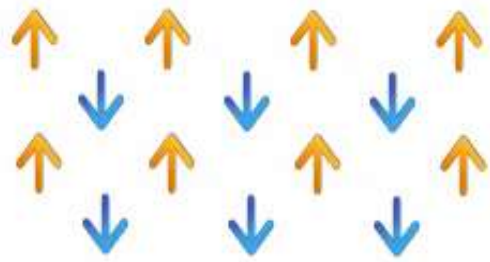
- In ferromagnetic materials, large magnetization occurs in the direction of the field.
 - Strong attraction is the characteristic property of ferromagnetism.
 - They exhibit spontaneous magnetization.
 - The relative permeability is very high .
 - The magnetic susceptibility is positive and very high.
 - Magnetic susceptibility is fairly high and constant up to a certain temperature according the equation $\chi = \frac{C}{T-T_c}$
- Where C = curie constant and T_c = Curie temperature.
- Ferromagnetism is due to the existence of magnetic domains which can be spontaneously magnetized.
 - Exhibit hysteresis phenomenon.
 - Spin alignment is parallel in the same direction of applied field.



Antiferromagnetic materials:

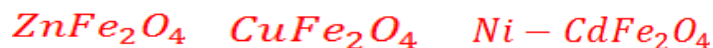
- These are crystalline materials.

- Susceptibility is positive and small.
- It varies with temperature.
- Below certain temperature ,materials are anti ferromagnetic.
- Above – paramagnetic
- Certain temperature – Neel temperature
- Spin allignment- Antiparallel
- Magnetic moment - Zero
- Examples: Ionic compounds (MnO,FeO,MnS ,etc.)



Ferri magnetic materials:

- They are ceramic materials and are good for electrical insulators(ferrites).
- Spin alignment –Antiparallel (not equal in magnitude)
- Magnetic moment –Small
- Spontaneous magnetization
- Susceptibility - Large (Positive)
- Ferrites consisting of ferric oxide. combined with one or more divalent metals.
- General formula written as MFe_2O_4
- M –divalent metal ions



Weiss domain theory of ferromagnetism:

The magnetic properties of ferromagnetic materials are explained on the basis of Weiss domain concept. The small region within which all spin magnetic moments are aligned in a specific direction is known as magnetic domain. Generally the size of domain will be of the order of the order of 10^{-6} m or larger. Each domain acts as a single magnetic dipole and is

oriented in random direction as shown in fig. the net magnetization is zero, in the absence of a magnetic field. Each domain is separated from other domains by a wall known as block or domain wall.

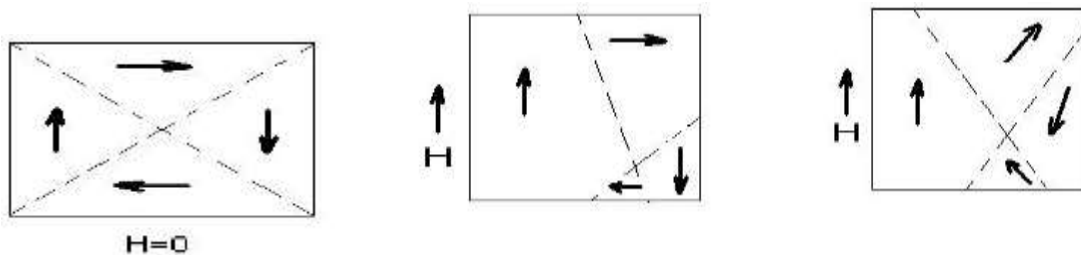
When a magnetic field is applied to the material, the alignment of a random domains are in two ways. such as

1. By motion of domain walls:

When an external magnetic field is applied, the domains which are parallel or nearly parallel to the applied field grow in size at the expense of other domains. The volume of the domains that are unfavorable the field decreases.

2. By rotation of domains

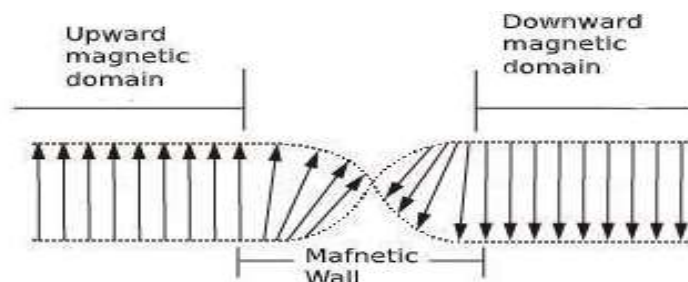
When the field is strong, rotation of the direction of magnetization occurs in the direction of the *field*.



Domain wall:

Let us consider two domains which are separated by a bloch or domain wall. The domains are opposite in direction. The second domain is obtained by rotating the first domain through 180° as shown in fig. The rotation of the domains is carried out gradually due to the existence of exchange force and anisotropy energy. In order to rotate the domain through an angle of 180° anisotropy energy requires a domain wall thickness of nearly $1 A^0$, whereas the exchange energy requires a large domain wall thickness.

However a minimum wall thickness is required with minimum potential energy at equilibrium condition. The minimum potential energy of the domain wall is known as domain wall energy.

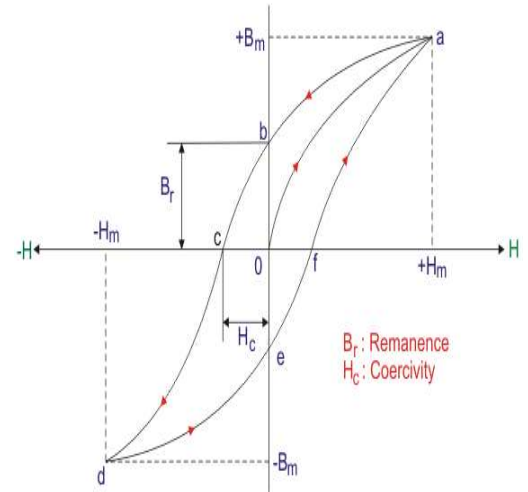


Hysteresis loop :

When a specimen of ferromagnetic material is placed in a magnetic field, the specimen is magnetized 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 as shown in fig.

The point O represents an initially unmagnetised specimen and a zero magnetic intensity. As H is increased, B also increases, but not uniformly, and a point such as 'a' is reached.

If H is now decreased, B also decreases but following a path 'ab'. Thus, B lags behind H . 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/remanence** of the specimen. Thus, the **Retentivity is a measure of the magnetic flux remaining in the specimen when the magnetising force is removed**.



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 force is called the **coercive force** or **coercivity** of the specimen. Thus, **Coercivity is a measure of the magnetic intensity required to reduce the residual magnetism of the specimen**.

As H is increase beyond 'oc'. the specimen is increasingly magnetised in the opposite diection, and a point such as 'd' is reached. By taking H back from its negative maximum value, through zero, to its original positive maximum value, a similar 'defa' is obtained. At point 'b' and 'e' where the specimen is magnetized in the absence of any external magnetic intensity, it is said to be a permanent magnet. It is thus found the flux density B always lags behind the magnetic intensity H .

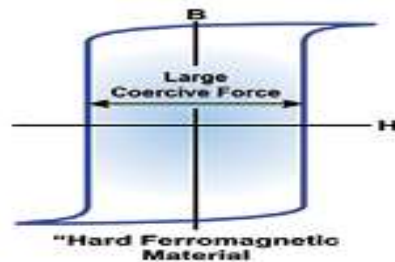
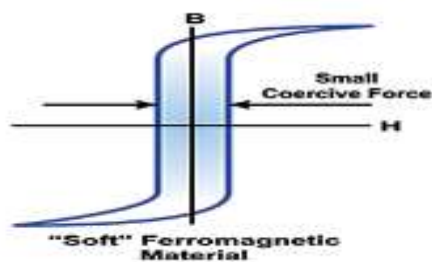
The lagging of B behind H is called hysteresis. The closed curve 'abcdefa' which represents a cycle of magnetisation of the specimen is known as the **Hysteresis curve** of the specimen.

Types of magnetic materials:

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

Soft and Hard Magnetic materials

Soft ferromagnetic	Hard ferromagnetic
<ol style="list-style-type: none"> 1. Can be easily magnetized or demagnetized 2. Thin and long hysteresis loop 3. High permeability and low coercive field 4. Large susceptibility & low remanent mag. 5. As area of the loop is small, magnetic energy loss per volume is less during magnetisation and demagnetisation 6. Application: electromagnet, in motors, generators, dynamos and switching circuits 7. Ex: Fe-Si alloy , Fe-Co-Mn alloy and Fe-Ni alloy 	<ol style="list-style-type: none"> 1. Can not be magnetised or demagnetised easily 2. Wide hysteresis loop 3. Low permeability and high coercive field 4. small susceptibility & high remanent mag. 5. Large area of the loop indicates, magnetic energy loss per volume is high during magnetisation and demagnetisation 6. For permanent magnet in speakers, clocks 7. Rare earth alloys with Mn, Fe, Co, Ni



Applications of Ferromagnetic materials:

The applications of ferromagnetic materials decides by the properties of retentivity ,coercivity and area of hysteresis loop.

1. **Permanent magnets:** The materials which are having high value of both retentivity and coercivity. Hard magnetic materials are used to make permanent magnets.
Ex: Steel.
2. **Electromagnets:** These are the magnets which can be turned on & off by switching the current on & off. The materials which shows high retentivity and low coercivity. Since such a material has to undergo magnetization and demagnetization again and again. The area of hysteresis loop should be small.
Ex: Soft iron
3. **Transformer cores:** For better inductive effect, the two coils of transformer are always wound on a core of ferromagnetic material. When AC is passed through primary coil of a transformer, the core of the transformer undergoes of large number of cycles of magnetisation and demagnetisation for every second. During

each cycle energy proportional to the area of hysteresis loop. The materials having narrow hysteresis loop is used.

Ex: Soft iron
