

## ***UNIT-3-Dielectric and Magnetic properties of materials***

### ***Syllabus:***

*Dielectric Materials- Introduction – Dielectric polarization – Dielectric polarizability, Susceptibility and Dielectric constant – Types of polarizations: Electronic, Ionic and Orientation polarizations (Qualitative) – Lorentz internal field – Clausius-Mossotti equation*

*Magnetic Materials- Introduction – Magnetic dipole moment – Magnetization – Magnetic susceptibility and Permeability – Origin of permanent magnetic moment – Classification of magnetic materials: Dia, para & Ferro-Domain concept of Ferromagnetism (Qualitative) – Hysteresis – Soft and Hard magnetic 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.

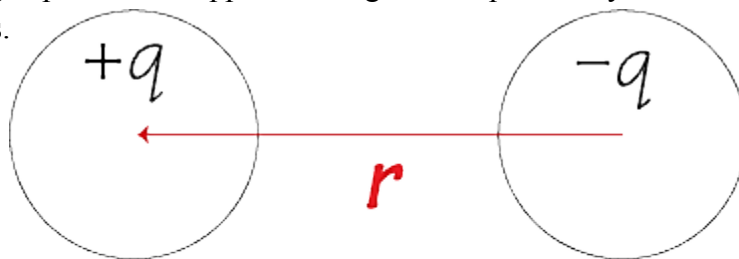
The difference between dielectric material and insulator depends on its application. Insulating materials are used to resist flow of current through it, on the other hand dielectric materials are used to store electrical energy. In contrast to the insulation aspect, the dielectric phenomena have become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

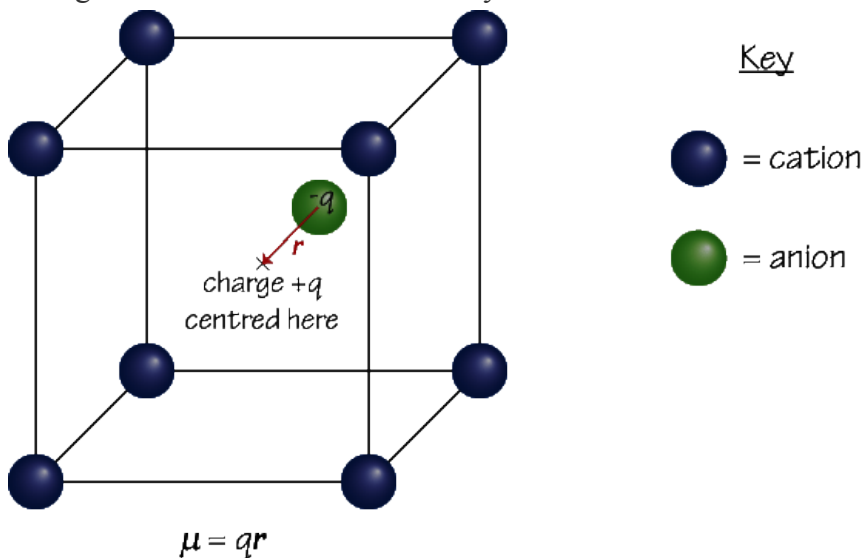
A dielectric supports charge by acquiring a polarisation in an electric field, whereby one surface develops a net positive charge while the opposite surface develops a net negative charge. This is made possible by the presence of electric dipoles – two opposite charges separated by a certain distance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

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

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

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

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

### ***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 ( $\epsilon_0$ ). It can also be defined as the ratio of the capacitance with dielectric ( $C_d$ ) and with air ( $C_A$ ) between the plates.

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

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

$$C = q / V = A \epsilon / d$$

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 creates a local dipole, creation of dipole by applying electric field is called as polarization.

Polarization is defined as induced dipole moment per unit volume.

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

### ***Polarisability***

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

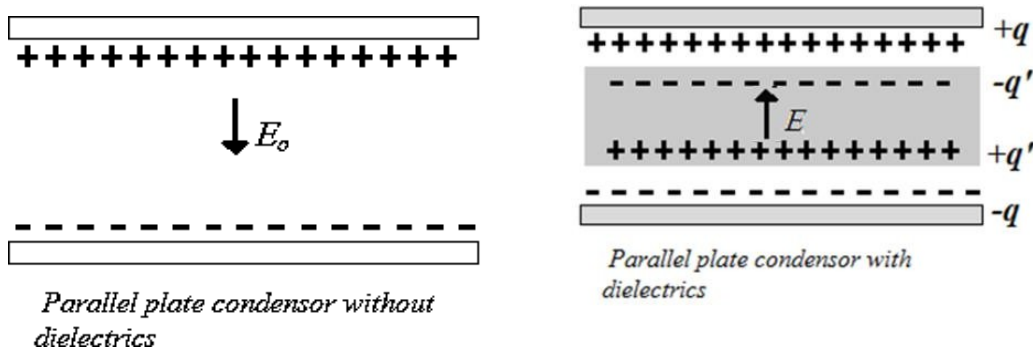
$$P \propto E$$

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

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,

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

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)

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

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

.....(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

$$P = E\epsilon_0(\epsilon_r - 1) \quad \dots(7)$$

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..)

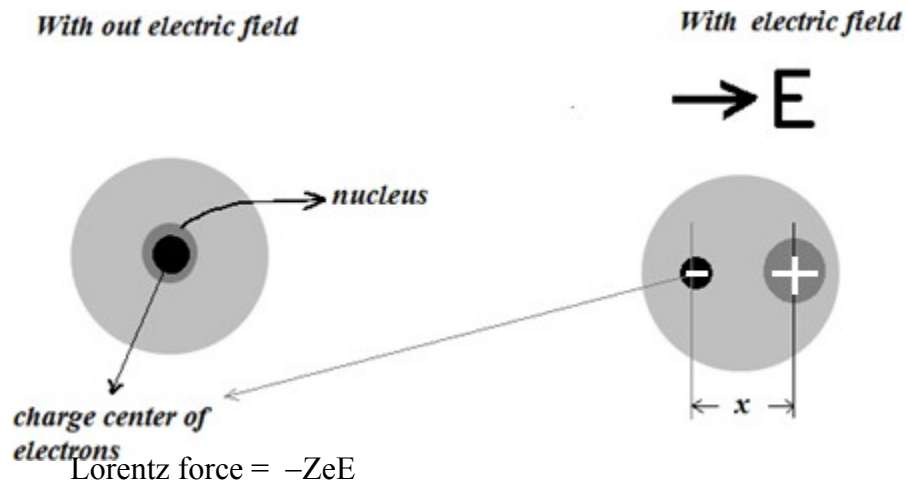
- It is independent of temperature.
- It occurs only at optical frequencies ( $10^{15}\text{Hz}$ )
- Vast fast process:  $10^{-15}\sim 10^{-16}\text{s}$ .

**Calculation of electronic polarizability:**

Electronic polarization can be explained by classical model of an atom in gasses. In gases 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  $x$ .



...(2)

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

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

From equation (1)

$$= \frac{4}{3}\pi x^3 \left[ -\frac{3}{4} \left( \frac{Ze}{\pi R^3} \right) \right]$$

$$= -\frac{Zex^3}{R^3}$$

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

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

$$\begin{aligned} -ZeE &= -\frac{Ze^2 x^2}{4\pi\epsilon_0 R^3} \\ x &= \frac{4\pi\epsilon_0 R^3 E}{Ze} \quad \dots(4) \end{aligned}$$

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

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

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

$$\mu_e \propto E$$

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

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

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

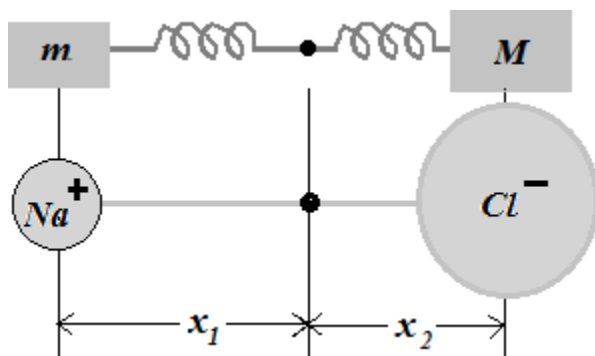
Where N is the number of atoms/m<sup>3</sup>

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

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

## ***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.



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

Let F be restoring force F

$$\propto x_1$$

$$\propto x_2$$

$$= \beta_1 x_1$$

$$= \beta_2 x_2$$

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  $x_1 = \frac{eE}{m\omega_0^2}$

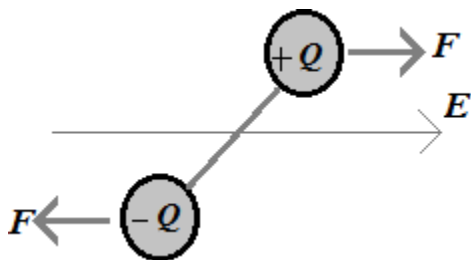
$x_2 = \frac{eE}{M\omega_0^2}$

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

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

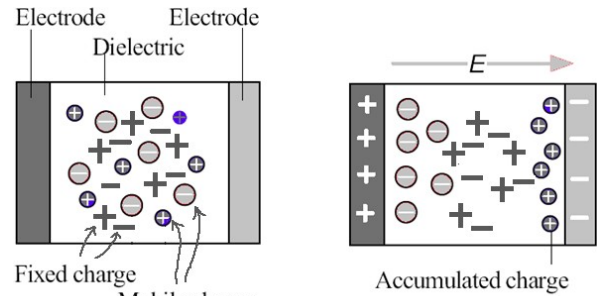
$$P_0 = \frac{N\mu_o^2 E}{3KT} = \alpha_o E \quad \dots(9)$$

Where  $\alpha_o = \frac{\mu_o^2}{3KT}$  is called as orientation polarisability ... (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.

*The internal field  $E$  must be equal to the sum of applied field plus the field produced at the location of the atom by the dipoles of all other atoms.*

$$\text{Internal field } E_i = E + \text{the field due to all other dipoles}$$

### Evaluation of internal field

The internal field at the atom site 'A' can be made up of four components  $E_1$ ,  $E_2$ ,  $E_3$  &  $E_4$ .

$$E_i = E_1 + E_2 + E_3 + E_4$$

### Field $E_1$ :

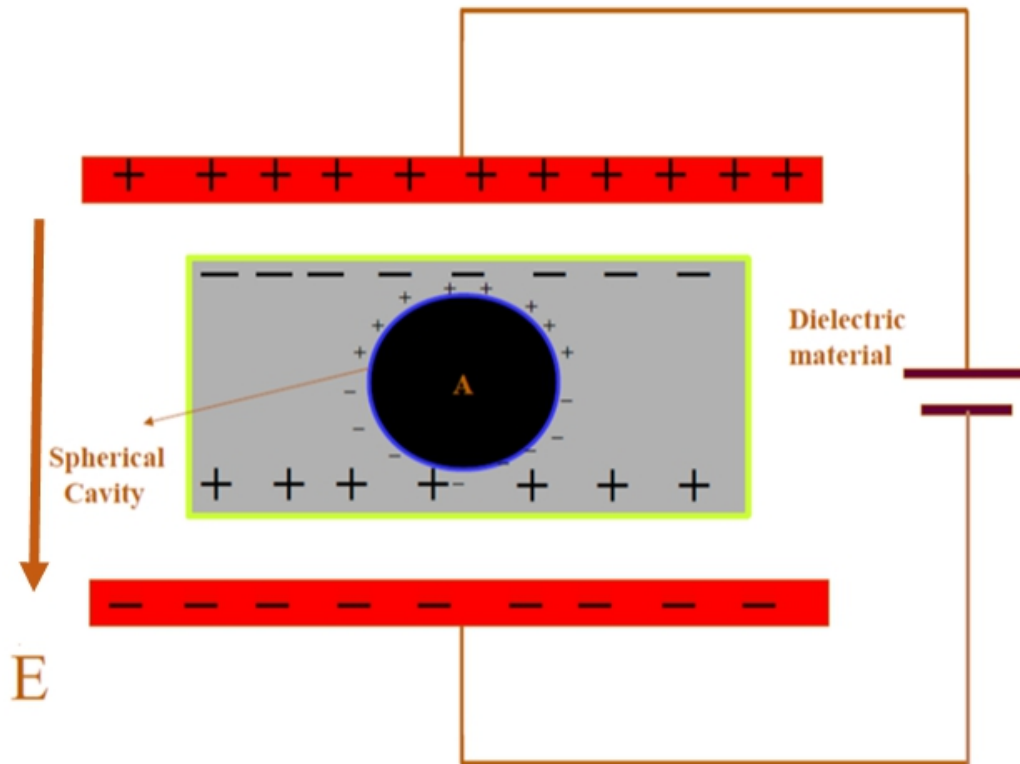
$E_1$  is the field intensity at A due to the charge density on the plates

$$E_1 = \frac{D}{\epsilon_0}$$

$$D = \epsilon_0 E + P$$

$$E_1 = \frac{\epsilon_0 E + P}{\epsilon_0}$$

$$E_1 = E + \frac{P}{\epsilon_0} \dots \dots \dots (1)$$



*Fig. Dielectric material placed in the electric field of intensity  $E$*

### Field $E_2$ :

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

$$E_2 = \frac{-P}{\epsilon_0} \dots \dots \dots (2)$$

### Field $E_3$ :

$E_3$  is the field intensity at A due to the atoms contained in the cavity, we are assuming a cubic structure, so  $E_3 = 0$ .

### Field $E_4$ :

1) This is due to polarized charges on the surface of the spherical cavity.



4) Thus the total field  $E_4$  due to the charges on the surface of the entire cavity is

$$\begin{aligned}
 E_4 &= \int_0^\pi dE_4 = \int_0^\pi \frac{P}{2\epsilon_0} \cos^2 \theta \cdot \sin \theta \cdot d\theta \\
 &= \frac{P}{2\epsilon_0} \int_0^\pi \cos^2 \theta \cdot \sin \theta \cdot d\theta \\
 &\text{let } x = \cos \theta \rightarrow dx = -\sin \theta d\theta \\
 &= \frac{-P}{2\epsilon_0} \int_1^{-1} x^2 \cdot dx \\
 &= \frac{-P}{2\epsilon_0} \left( \frac{x^3}{3} \right)_1^{-1} = \frac{-P}{2\epsilon_0} \left( \frac{-1 - 1}{3} \right) \\
 E_4 &= \frac{P}{3\epsilon_0}
 \end{aligned}$$

The internal field or Lorentz field can be written as

$$E_i = E_1 + E_2 + E_3 + E_4$$

$$E_i = \left( E + \frac{P}{\epsilon_0} \right) - \frac{P}{\epsilon_0} + 0 + \frac{P}{3\epsilon_0}$$

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

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

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

$$P = N\alpha_e E_i \quad \dots(1)$$

$$\alpha_e = \frac{P}{NE_i} \quad \dots(2)$$

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

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

By using the relation between the polarization and permittivity we have

$$P = E\epsilon_0(\epsilon_r - 1) \quad \dots(4)$$

$$E = \frac{P}{\epsilon_0(\epsilon_r - 1)} \quad \dots(5)$$

Substitute the value of  $E$  from (5) in (3)

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

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

$$\frac{\epsilon_r - 1}{\epsilon_r + 2} = \frac{N\alpha_e}{3\epsilon_0} \quad \dots(6)$$

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

# Magnetic Materials

## 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 . Wb/m<sup>2</sup>

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

### 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

### Origin of magnetic moment

In atoms, the permanent magnetic moments can arise due to the following:

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

#### Orbital magnetic moment of electron

Consider an electron of mass 'm', charge 'e' revolving around the nucleus in a circular orbit of radius 'r' in anticlockwise direction. Let 'v' be the linear velocity of electron and  $\omega$  be the angular velocity of a revolving electron. Then

the linear frequency of the revolving electron =  $\frac{\omega}{2\pi}$

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

The revolving electron in circular orbit establishes a current given by

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

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  $A = \pi r^2$ .

Then the corresponding magnetic moment is given by

$$\begin{aligned}\mu_{\text{orbital}} &= IA \\ &= e \frac{\omega}{2\pi} \pi r^2 \\ &= \frac{e\omega r^2}{2} = \frac{e}{2m} (m\omega r^2) \\ &= - \left( \frac{e}{2m} \right) (\text{orbital angular momentum})\end{aligned}$$

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

Angular momentum of electrons associated with orbital quantum number 'l' is given by  $l \left( \frac{h}{2\pi} \right)$ .

$$\begin{aligned}\therefore \mu_{\text{orbital}} &= - \left( \frac{e}{2m} \right) l \left( \frac{h}{2\pi} \right) \\ &= - \left( \frac{eh}{4\pi m} \right) l \\ &= - \mu_B l \quad \text{where } l = 1, 2, 3, \dots\end{aligned}$$

Where  $\mu_B = \frac{eh}{4\pi m}$  is a fundamental unit of magnetic moment known as Bohr magneton, its value is  $9.27 \times 10^{-24} \text{ Am}^2$ .

#### Spin magnetic moment of electron

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

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

Where ' $\gamma$ ' is the spin gyro magnetic ratio, and 'S' is the spin angular momentum. For an electron,  $S = \frac{h}{4\pi}$

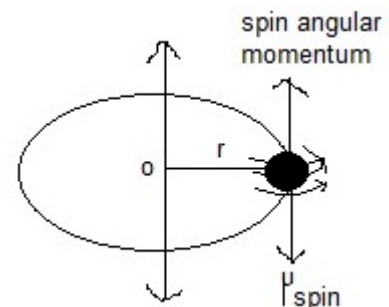
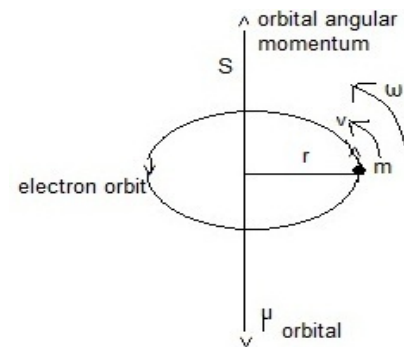
$$\mu_{\text{spin}} = \gamma \left( \frac{e}{2m} \right) \left( \frac{h}{4\pi} \right) = -9.4 \times 10^{-24} \text{ Am}^2$$

#### Magnetic moment due to nuclear spin

In addition to electronic contribution, nuclear spin also contributes to magnetic moment of atoms. The nuclear spin magnetic moment is given by

$$\mu_{\text{nuclear spin}} = \frac{eh}{4\pi M_p} = 5.05 \times 10^{-27} \text{ Am}^2$$

where  $M_p$  represents the mass of the proton.



## Bohr Magnetron

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

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

## 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

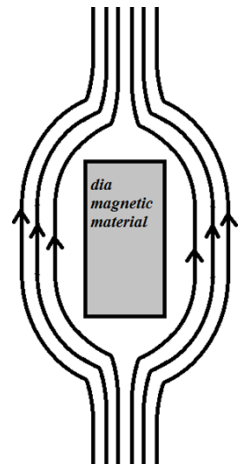
Ferri magnetic materials

## 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.

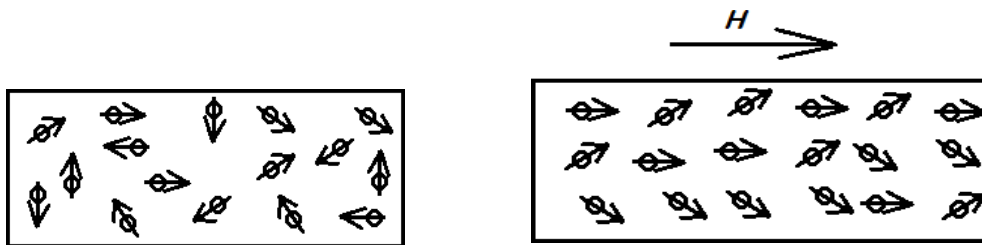


## Para magnetic materials.

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 constant 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

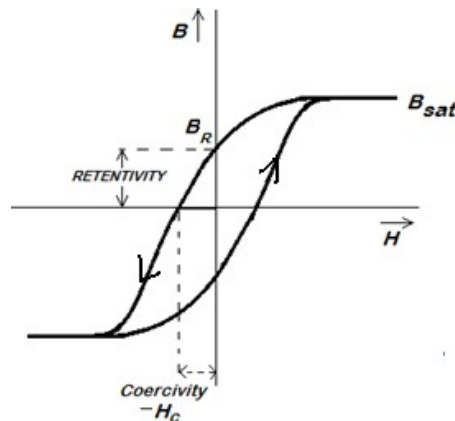
Atoms or molecules of ferromagnetic materials have permanent magnetic moment. In ferromagnetic materials all the dipoles are aligned parallel as shown in the figure if a small value of magnetic field is applied, a large value of magnetization is produced. As the ferromagnetic material have permanent 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  $\chi = \frac{C}{T - \theta_f}$

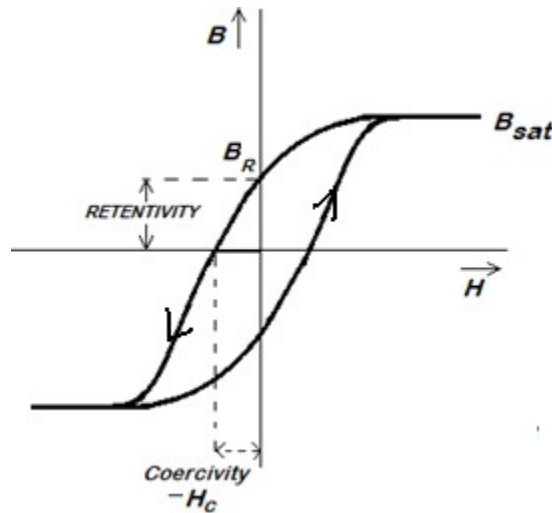
Where C is the Curie constant and  $\theta_f$  is the ferromagnetic Curie temperature. The transition and rare earth metals such as Fe ,Co, Ni ,Gd are the examples of ferromagnetic materials.



## 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 is 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 number of regions or domains ( $\approx 10^{-6}$  m or above) which are spontaneously magnetized. When 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 other by a wall known as 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 other by rotation of domain wall and domain growth is also reversible. Hysteresis curve is explained by domain concept.

**Antiferromagnetic materials :** These are the ferromagnetic materials in which equal number of opposite spins with same magnitude such that the orientation of neighbouring spins is in 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 antiferromagnetic material converts into paramagnetic material is known as Neel's temperature.

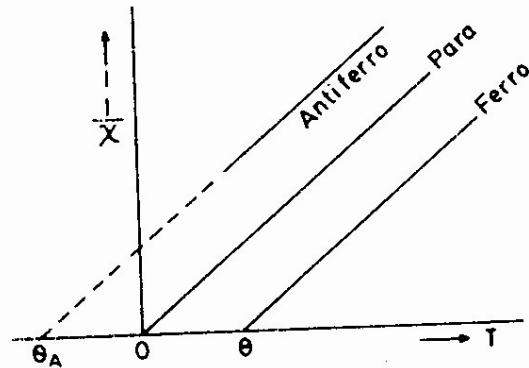
Examples: FeO, Cr<sub>2</sub>O<sub>3</sub>.

**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

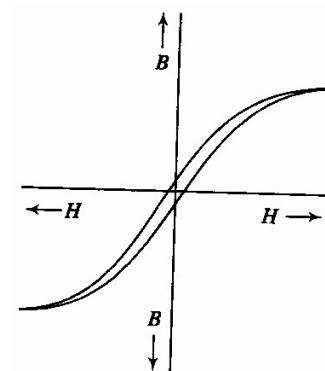
The magnetic materials that are easy to magnetize and demagnetize are called as soft magnetic materials.

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

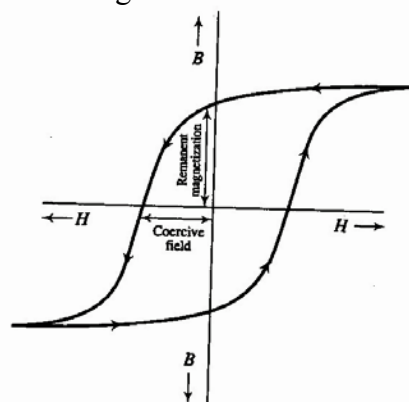
Applications of soft magnetic materials: Mainly used in electro- magnetic machinery and transformer cores. They are also used in switching circuits, microwave isolators and matrix storage of computers.

## 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. Derive an expression for internal field in solids and liquids. Or Derive an expression for internal field by Lorentz method?
5. Derive Clausius-Mossotti 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,  $\epsilon_r = 1$ .

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

When  $d$  is doubled and wax is inserted,

let the capacitance be  $C_2$ .

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

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

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 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,

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

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

The capacitance, the charge stored, the polarization and the displacement are 16.147 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,  $E = 500 \text{ V/m}$ .

**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  $18.4 \mu_B$ .

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

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