MAGNETISM AND DIELECTRICS

The fundamental thing responsible for electric field or magnetic field is charge. The static electric field is associated with charge. But we do not have magnetic charge in nature. A moving charge gives rise to a magnetic field.

In every atom electrons are revolving around the nucleus with –ve charge in electronic orbits create current in orbit. This current creates magnetic field. So atom or molecule behaves as a magnet. So that it consist of magnetic moment.

In magnetizing substances the net magnetic moment is not zero, but in non magnetizing substance like wood the net magnetic moment is zero.

MAGNETIC DIPOLE MOMENT (μ_M)

The arrangement of two equal and opposite charges separated by a distance is called magnetic dipole. The magnetic moment of a magnet is defined as the product of length of magnet (2l) and its pole-strength (m)

Magnetic moment $\mu_m = 2l \times m$ amp-m^2

It is vector quantity. Its direction is south to North Pole.

TORQUE (T)

Torque is defined as a couple acting on the bar magnet when placed at right angles to the direction of uniform magnetic field. Because of this torque magnetic dipole rotates and finally comes along the direction of field.

$\tau = \mu_m B \sin\theta$ where B is magnetic induction

Bar magnets, current loops, current carrying coils etc., all experience a torque in magnetic field and can be regarded as magnetic dipole.

MAGNETIC FIELD

The space around the magnet where its magnetic influence is experienced is called magnetic field. It is a scalar quantity.

MAGNETIC INTENSITY OR MAGNETIC FIELD STRENGTH (H)

Magnetic field intensity at any point in the magnetic field is defined as the magnetizing force experienced by a unit North Pole placed at that point. It is measured in *Amp/m.* It is a vector quantity. It is independent of the medium.

$H = \dfrac{F}{M}$

MAGNETISM AND DIELECTRICS

MAGNETIC INDUCTION OR MAGNETIC FLUX DENSITY (B)

The total no. of magnetic lines of force passing through the unit cross sectional area of the substance due to both magnetizing field and induced magnetism is called magnetic flux density.

$B = \dfrac{\phi}{A}$ It is vector quantity. It is measured in N/amp-m or wb/m^2 or Tesla.

INTENSITY OF MAGNETIZATION (I or M)

When a magnetizing substance is placed in an external magnetic field, the two ends of the substance acquire equal and opposite pole strength, hence substance possess some magnetic moment. The *induced magnetic moment per unit volume* of the substance when it placed in an external magnetic field is called intensity of magnetization. It is vector quantity and is measured in amp/m.

According to definition $I = \dfrac{Induced\, magnetic\, moment}{Volume}$

$$I = \dfrac{2lm}{A.2l} = \dfrac{m}{A} \ \ amp/m$$

So intensity of magnetization is defined as the *induced pole strength per unit area* of the substance when it is placed in an external magnetic field.

MAGNETIC PERMEABILITY (μ)

Permeability of a medium is *measure of the conducting power of the magnetic lines* of force through that medium. Consider a magnetizing substance is placed in uniform magnetic field. The magnetic lines of force passing through unit area in a substance is directly proportional to the field strength H. Therefore

B α H   B = μH

Where μ permeability of medium $\mu = \dfrac{B}{H}$

Permeability is the ratio of magnetic induction to field strength.

If the material is placed in air or free space then the above equation can be written as

$\mu_o = \dfrac{B_0}{H}$ where B_0 is flux density in air or free space, μ_o is permeability of air or free space, $\mu_o = 4\pi \times 10^{-7}$ H/m

$\mu_r = \dfrac{\mu}{\mu_0}$ is called relative permeability. It is the ratio of permeability of medium to permeability of air or free space.

For air and non magnetic materials $\mu_r = 1$.

MAGNETIC SUSCEPTIBILITY χ

The magnetic susceptibility of the specimen gives *how free the specimen can be magnetized*. The intensity of magnetization I or M of the substance is directly proportional to the magnetic intensity H.

i.e., M α H or M = χH

where χ is proportionality constant known as magnetic susceptibility.

$\chi = \dfrac{M}{H}$ dimension less quantity.

MAGNETIZATION

The term Magnetization is defined as the process of converting non-magnetic material into magnetic material.

RELATION BETWEEN RELATIVE PERMEABILITY μ_r AND SUSCEPTIBILITY χ

When a material is placed in an external magnetic field, the total flux is sum of the flux in air or free space produced by external field and flux in free space produced by magnetization of the material.

$B = B_0 + B_i$

B_0 = flux in air or free space due to external field = $\mu_0 H$
B_i = flux in air or free space due to induced magnetism = $\mu_0 I$

$B = \mu_o[\ H + I\ ]$ --------(1)

This is the relation between B, H and I.

Divide the above equation by H, we get

$\dfrac{B}{H} = \mu_o\left[\ 1 + \dfrac{I}{H}\ \right]$

$$\mu = \mu_o(1 + \chi) \qquad \frac{\mu}{\mu_0} = 1 + \chi$$

$$\mu_r = 1 + \chi \text{ ---------- } (2)$$

SPIN MAGNETIC MOMENT

A spin magnetic moment is the magnetic moment induced by the spin of elementary particles. For example, the electron is an elementary spin-1/2 fermion. Quantum electrodynamics gives the most accurate prediction of the anomalous magnetic moment of the electron.
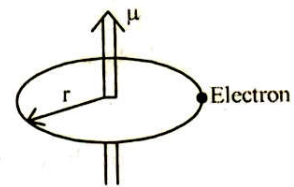
ORIGIN OF MAGNETIC MOMENT

Every substance is made with large number of molecules or electrons. The magnetic properties of the materials are due to the motion of the electrons around the nucleus in the atoms. Every electron is associated with the orbital and spin motions. The orbital motion of the electron around the nucleus is imagined as current carrying circular having no resistance. As a result it sets up the magnetic field around the atom. Hence every atom in the material acts as a tiny magnet. In general the magnetic moment of atom originate from 3 sources:

1) Orbital **magnetic moment** of the electrons

2) Spin magnetic moment of the electrons

3) Spin magnetic moment of the Nucleus

Orbital Motion of Electrons: Bohr Magneton

The motion of the electron constitutes a current and the circular path of electron is identical to current loop. Such a current loop behaves as an elementary magnet having magnetic moment. The total orbital magnetic moment of magnetic moment of an atom is sum of orbital magnetic moments of individual electrons.

Let us consider an atom in which there is single electron of mass m and charge e revolving around the positive nucleus in a circular orbit of radius r. Let v be the velocity of electron, ω be the angular velocity of the electron. The magnetic moment possessed by an electron which is revolving around the nucleus is given by

Magnetic moment $\mu_m = I \times A \text{ ------------ } (1)$

where I is current in the circular loop of orbit. A$= \pi r^2$ is the area enclosed by the circulating current.

We know $I = \dfrac{ev}{2\pi r}$, r is the radius of the circular orbit   (I = e /t, t = distance/speed)

From equ. (1), $\mu_m = \dfrac{ev}{2\pi r}\pi r^2$

$$= \dfrac{evr}{2} \text{ ---------- (2)}$$

The angular momentum of the electron in the circular orbit of radius r is L = mvr or r = L/mv

From equ (2),   we get $\mu_m = -\dfrac{eL}{2m}$ ----------- (3)

The negative sign indicates that the dipole moment is opposite to the vector representing the angular momentum.

The constant $\dfrac{e}{2m}$ *is called **gyromagnetic ratio**.* It is the ratio of magnetic moment to angular momentum.

According to the modern atomic theory the angular momentum of electron in the orbit is determined by the orbital quantum number l which is restricted to a set of values $l = 0, 1, 2….$ (n -1). Where n is principal quantum number. Which determine the energy of orbit. It can accept only integers.

The angular momentum of electron associated with a particular value of '*l*' is $\dfrac{lh}{2\pi}$

$$\therefore \; \mu_m = -\left(\dfrac{e}{2m}\right)\dfrac{lh}{2\pi} \; = -\left(\dfrac{eh}{4\pi m}\right)l \; = -\mu_B.\, l \text{ -------- (4)}$$

The quantity $\mu_B = \left(\dfrac{eh}{4\pi m}\right)$ is called Bohr magneton and has value 9.27×10^{-24} A-m^2

Bohr magneton is a fundamental unit of atomic magnetic moment. Electron possess the magnetic moment not less than Bohr magneton. For filled electronic shells the total angular momentum is zero.

$\therefore$ Atoms or ions which are having only filled shells have no permanent magnetic moment, they are diamagnetic.

Spin Motion of Electron

The spinning electron also associated with a magnetic moment, which is given by the relation $\mu_{es} = \gamma\left(\dfrac{e}{2m}\right)$S, where γ is spin gyromagnetic ratio depends on the structure of the spinning

particle, experimental value of γ = -2.0024, the negative sign indicates that μ_{es} is opposite to that of S in direction. Since S = $\dfrac{h}{4\pi}$ for electron, μ_{es} = 9.24 x 10^{-24} A-m^2

Spin magnetic moment of Nucleus

The magnetic moment of the nucleus is given by μ_{ps} = $\dfrac{eh}{4\pi M_p}$ = 5.05x10^{-27} A-m^2 where M_p

represents the mass of proton which is nearly 1/2000 as much as that of an electron. The magnetic moment due to the nuclear spin is neglected. The two factors namely orbital motion and spin motion of electron are contributed to the permanent magnetic moment in atoms.

CLASSIFICATION OF MAGNETIC MATERIALS BASED ON ATOMIC MAGNETIC MOMENT

The materials may be classified on the basis of permanent magnetic moment in to five groups. Magnetic properties other than diamagnetism, which is present in all substances, arise from the interactions of unpaired electrons. Is as shown in the figure

Diamagnetic
Materials composed of atoms or molecules having zero magnetic moment are called **diamagnetic.**

Paramagnetic
If the atomic magnetic dipoles are orient in random direction in the absence of external field, the material will be paramagnetic. The orientation of magnetic moments in paramagnetic substances is as shown in fig A.
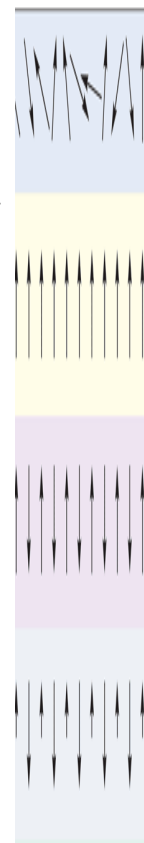
Ferromagnetic
If the individual dipoles of the material orient in the same direction, the material will be Ferro magnetic. The orientation of dipole moment in ferro magnetic materials is shown in fig B.

Antiferro magnetic
If the neighboring dipoles in the material orient in opposite direction to each other and with same magnitude, the materials are called antiferro magnetic as shown in fig C.

Ferri magnetic
If the neighbouring dipoles are orient anti parallel and with unequal magnitudes, the materials are called ferri magnetic as shown in fig D.
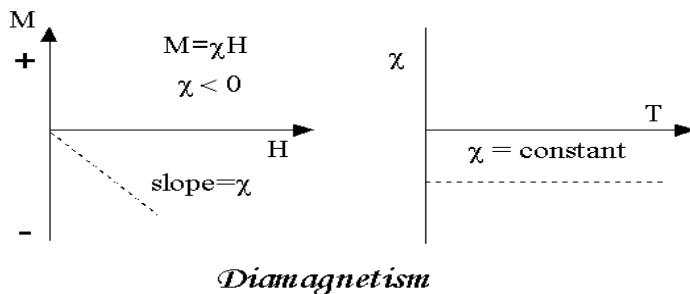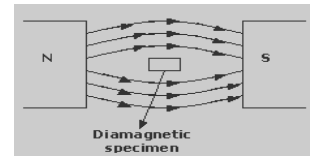
DIAMAGNETIC MATERIALS

The materials which are magnetized in the direction opposite to the magnetic field are called diamagnetic materials. or The materials which cannot be magnetized in the external magnetic field are called diamagnetic materials.

Examples: All inert gases, hydrogen, air, water, gold, silver, bismuth etc.,

Properties

- Diamagnetic substances exhibit negative susceptibility. The value of susceptibility is small and is the order of 10^{-6}

- As the diamagnetic susceptibility is negative, the relative permeability μ_r is slightly less than unity.

- When a small rod of diamagnetic material is placed in magnetic field it turns to a position perpendicular to the field lines. Diamagnetic materials pulled aside the field lines

- The magnetic susceptibility of diamagnetic materials is independent of temperature.

Note that when the field is zero the magnetization is zero. The other characteristic behavior of diamagnetic materials is that the susceptibility is temperature independent. Some well known diamagnetic substances, in units of 10^{-8} m^3/kg, include: quartz (SiO2) -0.62 ,Calcite (CaCO3) -0.48 ,water -0.90

- The magnetization varies linearly with the applied field H, when the field is too strong.

- When the diamagnetic substance is placed in non uniform magnetic field, it move towards the weaker region of the field.

- The lines of force show less preference to pass through these substances than through vacuum or air.

- The liquid level of diamagnetic solution solution taken in the U-tube depresses when it is placed in a uniform magnetic field as in below
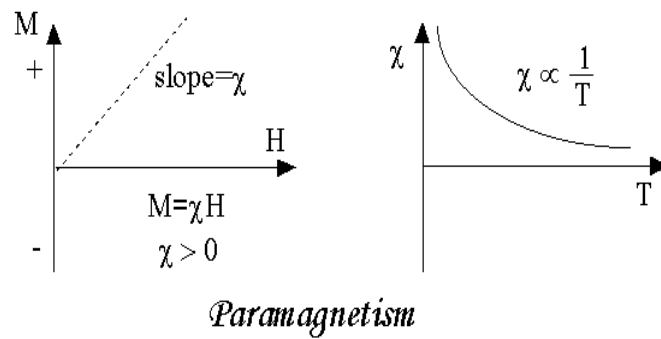
PARAMAGNETIC MATERIALS

Materials or substances which acquire weak magnetism in the direction of the field when placed in magnetic field are called paramagnetic materials.

Examples: oxygen, solutions of iron salts, copper chloride, chromium and platinum.

Properties

- Paramagnetic materials exhibit +ve magnetic susceptibility, the susceptibility is of the order of 10^{-3}
- The relative permeability μ_r is slightly more than unity and move from the region of low intensity to high intensity in magnetic field.
- A paramagnetic material magnetized in the direction of field. Field lines are pulled towards the materials and penetrate through the material when it is placed in a magnetic field.

- The paramagnetic susceptibility is positive. It is dependent on temperature. The susceptibility is inversely proportional to temperature. Thus

$$\chi_{para} = \frac{c}{T} \quad \text{where c is curie's constant and relation is called curie's law.}$$

Paramagnetism

At normal temperatures and in moderate fields, the paramagnetic susceptibility is small (but larger than the diamagnetic contribution). Unless the temperature is very low (<<100 K) or the field is very high paramagnetic susceptibility is independent of the applied field. Under these conditions, paramagnetic susceptibility is proportional to the total iron content. Many iron bearing minerals are paramagnetic at room temperature. Some examples, in units of 10-8 m3/kg, include: Montmorillonite (clay) 13 Nontronite (Fe-rich clay) 65 Biotite (silicate) 79 Siderite(carbonate) 100 Pyrite (sulfide) 30.

- The magnetization M varies linearly with the applied field when the field is not too strong.
- In no uniform field the paramagnetic substances are attracted towards stronger region of magnetic field.

- The liquid level of diamagnetic solution taken in the U-tube rises when it is placed in uniform magnetic field as shown.

FERRO MAGNETIC MATERIALS

Materials which are strongly magnetized in the direction of the field in external magnetic field are called ferromagnetic.
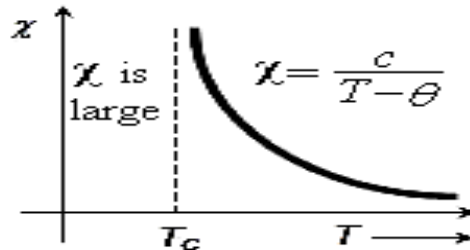Example: Iron, Nickel, Cobalt and some steels are examples.

Properties

- Ferro magnetic materials exhibit very high values of magnetic susceptibility and relative permeability.

- These are very strong the dipoles line up permanently upon the application of external field.

- The magnetic susceptibility and relative permeability are positive and exhibit very high values Susceptibilities are in the order of 10^6 and relative permeabilities are of the order of 10^3.

- They conduct magnetic flux much as metals conduct electric current.
- They do not exhibit a linear proportionality between the magnetization and the field strength.
- The magnetization of these materials is not unique function of field strength but depends on the field to which it is subjected to.

- When ferro magnetic material is kept in magnetic field, the field lines crowd in to the material.
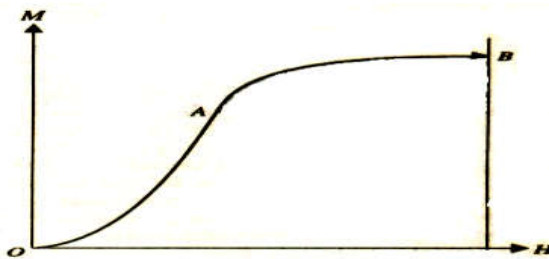

- As the temperature increases susceptibility decreases, above a certain temperature ferromagnetic material become ordinary paramagnetic and this temperature is called curie temperature.

  Susceptibility follows the curie's law. $\chi = \dfrac{c}{T - \theta}$, where θ is paramagnetic curie's temperature. For $T > \theta$ material transforms into paramagnetic state, $T < \theta$ material is in ferromagnetic state.

- **Magnetization M varies non linearly with applied field H. as M varies non linearly with the applied field, μ_r also increases with increase of field, beyond the saturation point permeability decreases rapidly as shown in fig.**

- Ferromagnetic material exhibit hysteresis.

WEISS MOLECULAR FIELD THEORY (Spontaneous magnetization in ferromagnetic materials)

According to Weiss spontaneous magnetization in a ferromagnetic substance is due to the interaction between the atomic dipoles in the domain. This interaction produces internal molecular field H_i. Due to this internal field, the spins would be parallel to the field.

$\therefore$ $H_i \propto M$ or $H_i = \gamma M$ where γ is weiss constant.

$\therefore$ Effective field (total field) $H_{eff.} = H + H_i$

$$H = H + \gamma M \quad \text{----------} \quad (1)$$

Where H is applied field and γ is called molecular field constant which is also known as Weiss constant. According to Weiss theory every Ferro magnetic substance should initially exhibit paramagnetism.

∴ Susceptibility of Paramagnetism $\chi = \dfrac{M}{H} = \dfrac{c}{T}$

For Ferromagnetic substance, $\quad \chi = \dfrac{M}{H_{eff}} \chi = \dfrac{M}{H + \gamma M} = \dfrac{c}{T}$

$$MT = Hc + \gamma cM \quad \text{or}$$

$$M(T - \gamma c) = Hc \quad\quad \text{or}$$

$$\dfrac{M}{H} = \chi = \dfrac{c}{T - \gamma c} = \dfrac{c}{T - \theta} \text{ --------- (2)}$$

Where θ = γc. From equ (2) it is clear that magnetization tends to infinity at T = θ. It means that the interaction of the individual magnetic moments reinforce each other causing them to align parallel at T = θ. Where c is the curie constant, θ is the curie temperature of ferromagnetic material. This relation is called curie weiss law. For all the temperatures T< θ the materials behave like ferromagnetic. For temperature T > θ, the materials changes into paramagnetic state.

DOMAIN HYPOTHESIS

In order to explain theory of ferromagnetism weiss introduced the new concept of magnetic domains. Weiss postulated that *entire ferromagnetic material split into a large no. of small regions of spontaneous magnetization. These regions are called domains.* Every domain possesses **a definite value and direction of the magnetic moment. Each Domain** has a size ranging from 10^{-9} to 10^{-9} m^3 and contains 10^{17} to 10^{21} atoms and whose magnetic axes are aligned

in the same direction even in the direction even in the absence of magnetic field. In the absence of an external filed the magnetic moment vectors are randomly oriented and net magnetic moment is zero. When magnetic field is applied the domains rotate and make to align their magnetic moments with the field direction. So specimen exhibits a net magnetization.
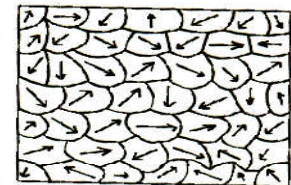

Fig. Ferromagnetic domains

When an external field is applied to a ferromagnetic material the magnetization in the material is increased in two ways.

1. Due to displacement of the boundaries of the domains

An unmagnetized ferromagnetic specimen is as shown in the fig (a) .when the specimen is placed in the magnetic field the domains the domains parallel or nearly parallel to the filed direction H, can grow in size as shown in fig (b).
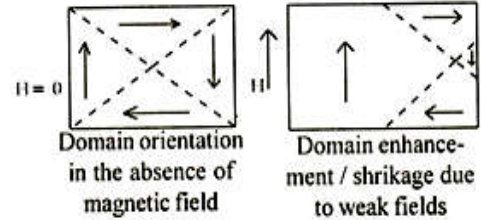

Domain orientation in the absence of magnetic field

Domain enhance-ment / shrikage due to weak fields
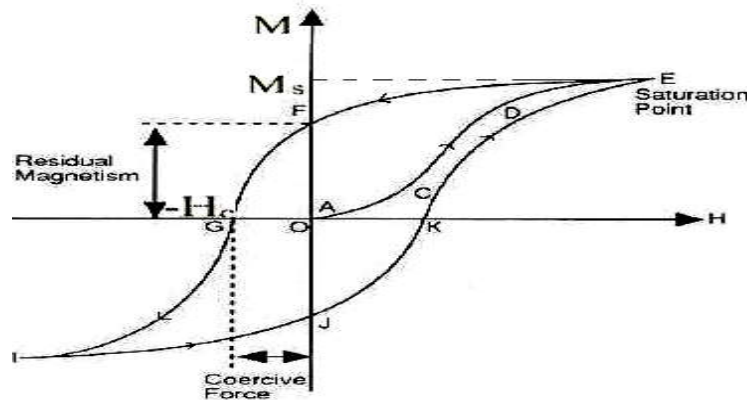
Fig (a)   Fig (b)

2. Due to rotation of Domains

The domains rotate until magnetic moments are more or less aligned in the direction of external magnetic field as shown in the figure.

HYSTERISIS

Hysteresis means Lagging   i.e., The Lagging of intensity of magnetization (I) behind the intensity of magnetic field (H). **The plot of Magnetization M or Magnetic field B as a function of Magnetic Field Intensity H (i.e. M-H or B-H graph) gives the Hysteresis curve.**

Consider an unmagnetised ferromagnetic substance (iron bar) is placed in a magnetising field. When the bar is slowly magnetized the variation in the intensity of magnetization I is shown in the fig. When the substance is slowly magnetised, then magnetic induction B increases nonlinearly along the curve (OACDE) called as the magnetization curve. At point E almost all of the magnetic domains are aligned parallel with the magnetic field. An additional increase in H does not produce any increase in B. E is called as the point of magnetic **saturation** of the material.

H is decreased till it reduces to zero. B reduces from its saturation value at "E" to that at point "F". Some of the magnetic domains lose their alignment but some maintain alignment i.e.

Some magnetic flux density B is still retained in the material. When the field H is switched off the curve does not retrace in its original path. At zero field there exists a residual field called remanent flux or retentivity (OF).

To bring back the magnetization zero the magnetic field is applied in reverse direction H is reversed in this case the curve EFH is obtained which is called coercive field H_c. The amount of intensity of magnetic field applied in the reverse direction to remove the **retentivity** is known as **Coercivity or Coercive force.** It is represented as OG in the graph. Further repeating the process the remaining portion [HIJKEA] in the graph is obtained. The closed loop [OABCDEFGHIJA] is called Hysteresis loop (or) (I - H) curve. For one cycle of magnetization, now the material is taken out. After a cycle of magnetization, there is some expenditure (loss) of energy. This loss of energy is radiated in the form of heat energy in the material. This loss of energy is directly proportional to the area of the loop.

From the hysteresis loop, a number of primary magnetic properties of a material can be determined.

1. **Retentivity** - A measure of the residual flux density corresponding to the saturation induction of a magnetic material. In other words, it is a material's ability to retain a certain amount of residual magnetic field when the magnetizing force is removed after achieving saturation. (The value of **B** at point b on the hysteresis curve.)

2. **Residual Magnetism** or **Residual Flux** - the magnetic flux density that remains in a material when the magnetizing force is zero. Note that residual magnetism and retentivity are the same when the material has been magnetized to the saturation point. However, the level of residual magnetism may be lower than the retentivity value when the magnetizing force did not reach the saturation level.

3. **Coercive Force** - The amount of reverse magnetic field which must be applied to a magnetic material to make the magnetic flux return to zero. (The value of **H** at point c on the hysteresis curve.)

4. **Permeability, m** - A property of a material that describes the ease with which a magnetic flux is established in the component.

5. **Reluctance** - Is the opposition that a ferromagnetic material shows to the establishment of a magnetic field. Reluctance is analogous to the resistance in an electrical circuit.

SOFT AND HARD MAGNETIC MATERIALS:
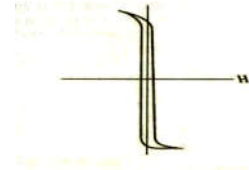
Soft or Type-I Magnetic Materials

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

Properties:

- The fig. shows the nature of hysteresis loop of soft magnetic material.

- They have small hysteresis loss due to small area of hysteresis loop area.

- These materials having large values of permeability and susceptibility

- Coercivity and retentivity are small.

- These materials are free from irregularities

- Its magneto static energy is small.

- They are used in Electromagnetic machinery and in transformer's cores, switching circuits, Microwave isolators, shift registers and to produce electromagnets
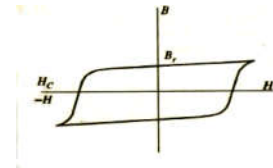 Examples: Fe-Ni alloy, Fe-Si alloy

Hard or Type-II Magnetic Materials

Materials which are hardly magnetized and demagnetized are called hard magnetic materials. The fig. shows the nature of hysteresis loop of hard magnetic materials.
Properties:

- They have large hysteresis loss due to large hysteresis loop area.

- These materials have small values of permeability and susceptibility.

- Coercivity and retentivity are high.

- In these materials the irregularities in the structure are more.

- Its magneto static energy is more

- They are used to produce permanent magnets which are used in magnetic detectors, microphones, flux meters, voltage regulators, damping devices etc.,
  Examples: Al-Ni-Co alloy, Cu-Ni-Co alloy.

FERRO ELECTRICITY:

Certain crystals exhibit spontaneous polarization in the absence of electric field is called ferro electrics and this phenomenon is called ferro electricity. In ferro electric crystals the centers of positive and negative charges do not coincide with each other even in the absence of the field, thus producing non zero value of dipole moment.
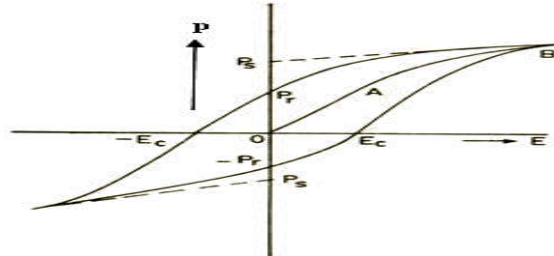
Examples: Rochellle salt ($NaK.C_4H_4O_6.4H_2O$), Barium Titanate ($BaTiO_3$),
Di HydrogenPotassium Phosphate (KH_2PO_4), Potassium Niobate etc.

Properties:

1. The ferro electricity disappears above a certain temperature called transition temperature or the Curie point T_c, material transforms into Para electric state by rapid decrease in the dielectric constant with increase in temperature.

2. In ferro electrics, polarization P varies nonlinearly with the applied field E. where as in ordinary dielectrics P varies nonlinearly with the applied field E. So ferro electrics are called non linear dielectrics and ordinary dielectrics are linear dielectrics.

3. Ferro electrics exhibit hysteresis. When a virgin ferro electric crystal is subjected to an alternating electric field the polarization P increases nonlinearly with the applied field E and reaches saturation at a certain value of polarization. The polarization does not change even if E is further increases. If the field is switched off, polarization does not tends to zero and having some *residual polarization*. This is also called *remanent flux.*

To bring back this polarization to zero value, electric field must be applied in opposite direction, called *coercive field* E_c. Further increase in the field, saturation value of polarization also occurs in negative direction also. Further increase in field, a closed loop is obtained as shown in fig. called hysteresis loop. Above transition temperature hysteresis loop disappears and the crystal behaves like ordinary dielectric.

4. All ferro electrics exhibit pyro electricity and piezo electricity but all pyro and piezo electrics need not to be ferro electric. For example tourmaline is pyro electric and not ferro electric. Quartz is piezo electric but not ferro electric.

5. Ferro electric crystals exhibit birefringence, i.e. double refraction when a plane polarized light is passed through them.
Note: Certain crystals exhibit polarization when they are subjected to heat are called pyro electric.
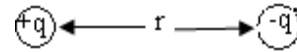
Applications:
1. Ferro electric materials possess high value of dielectric constant, so they are used to produce small sized and high capacitance capacitors.
2. Ferro electric materials show piezo electricity, so they are used to produce and detect sound waves.
3. Ferro electric materials also show pyro electricity, so they are used to detect infrared radiation.
4. Ferro electrics show hysteresis property, so they are used to construct memory devices in computers.

MAGNETISM AND DIELECTRICS

DIELECTRICS

Dielectrics are nothing but insulators in which there are no free electrons for conduction. In dielectrics forbidden energy is greater than 6ev.

Electric Dipole

The arrangement of equal and opposite charges separated by a distance is called electric dipole or dipole.

Dipole Moment

Electric dipole moment is product of magnitude of charge and distance of separation between the two charges. If q is the magnitude of the charge and r is the distance of separation, the dipole moment is given by

$\mu_e = q \times r$ coulomb-meter

Nonpolar Dielectrics

In an atom or molecule, if the center of gravity of positive charge coincides with the center of gravity of negative charge, the distance of separation between two charges is zero. The net dipole moment is zero ($\mu_e = q \times 0 = 0$). Such a molecule is called nonpolar molecule and medium formed by these molecules is called nonpolar dielectric.
Ex. H_2, N_2, Co_2, CH_4, C_6H_6 etc.

Polar Dielectrics

When two or more atoms form a molecule and if the center of gravity of positive charge do not coincide with that of negative charge, molecule possess some permanent dipolemoment such molecule is said to be polar molecule. The medium formed by these molecules is called polar dielectric.
Example: H_2O, HCl, N_2O, NH_3……

DIELECTRIC CONSTANT OR RELATIVE PERMITTIVITY ε_r

Let us consider a parallel plate capacitor connected to voltage source V_0. Let the charges on the plates be $+Q_0$ and $-Q_0$.
The capacitance of the capacitor when no medium is placed between the plates is

$$C_0 = \frac{\varepsilon_0 A}{d}$$ ------- (1) where 'd' is distance of separation between the plates and 'A' is area of the plate.

When the plates of the condenser are disconnected from the voltage source, the magnitude of charge Q_0 on either plate must remain constant. When the dielectric is placed between the plates of the condenser, the potential difference decreases to a value V and capacitance of the condenser increases to 'C'.

$$\therefore C = \frac{\varepsilon A}{d} \text{ where } \varepsilon \text{ is permittivity of the medium.}$$

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d} \quad = \varepsilon_r C_0$$

Dielectric Constant or relative permittivity $\varepsilon_r = \dfrac{C}{C_0}$

So dielectric constant is defined as the ratio of the capacity of the condenser with dielectric between the plates to the capacity of the condenser with air or vaccum in between the plates. It is also defined as the ratio of permittivity of the medium to the permittivity of the air or free space.

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \quad \text{where } \varepsilon_0 = 8.854 \times 10^{-12} \text{ F/m or } C^2/\text{N-m}^2 \text{ is permittivity of air or free space.}$$

FIELD VECTORS IN DIELECTRICS

ELECTRIC FIELD INTENSITY (E)

Electric field intensity at any point in the electric field is defined as the force experience by unit positive charge placed at that point. Let 'F' be the force acting on a charge 'q' then according to definition,

$$\bar{E} = \frac{\bar{F}}{q} \text{ N/coulomb}$$

The direction of 'E' is same as direction of $\bar{F}$

DIELECTRIC POLARIZATION ($\bar{P}$)

The induced dipole moment per unit volume of the dielectric medium placed in the external field is called dielectric polarization $\bar{P}$

i.e. $\bar{P} = \dfrac{\mu}{V}$ --------- (1) where V is the volume of dielectric

It is vector quantity whose direction is induced negative charge to induced positive charge.
But induced dipole moment is the product of induced charge and distance of separation between the charges.

If q^1 and l are the induced charge and length of the dielectric (distance of separation),

$$\bar{P} = \frac{q^1 \, x \, l}{A \, x \, l} = \frac{q^1}{A} \ \text{C/m}^2 \qquad (\because V = \text{area x length})$$

Thus electric polarization is also equal to the induced charge per unit area

ELECTRIC DISPLACEMENT ($\bar{D}$) :

Electric displacement is nothing but electric flux density. i.e. electric lines of force per unit area. Mathematically it can be written as real charge per unit area of the conducting surface. Let a charge 'q' be uniformly distributed on a conducting surface of area 'A',

$$D = \frac{q}{A} \ \text{C/m}^2 \ \text{ or } q = D\,A. \qquad \text{In integral form} \quad q = \oint D.\bar{ds}$$

The electric displacement is also equal to the product of absolute permittivity of the medium (ε) and resultant electric field intensity E

i.e. $\bar{D} = \varepsilon\,E$

ELECTRIC SUSCEPTIBILITY (χ_e)

The electric polarization P is proportional to the electric field intensity E $\therefore P \propto E$ or $P = \varepsilon_0 \chi_e E$ where χ_e is proportionality constant called electric susceptibility

$$\chi_e = \frac{P}{\varepsilon_0 E}$$

RELATION BETWEEN χ_E AND ε_R

Consider a parallel plate condenser of plate area 'A'. let it be completely filled with a dielectric. Let the magnitude of the real charge on either plate is 'q' coulombs. Let a charge of magnitude 'q^1' is induced on the dielectric faces as shown in figure.

Let 'E' be the electric field intensity. According to Gauss law in electrostatics,

$$\oint_S \bar{E}.\bar{ds} = \frac{q - q^1}{\varepsilon_0} \quad \text{or}$$

$$E.A = \frac{q - q^1}{\varepsilon_0}$$

$$\Rightarrow \varepsilon_0 E = \frac{q}{A} - \frac{q^1}{A} \quad \text{or} \quad \varepsilon_0 E = D - P$$

$$\boxed{\bar{D} = \varepsilon_0 E + \bar{P}} \text{ ----------- (1) This is the relation between D, E and P}$$

Dividing the above equation by $\varepsilon_0 E$, we get

$$\frac{\bar{D}}{\varepsilon_0 \bar{E}} = 1 + \frac{\bar{P}}{\varepsilon_0 E}$$

$$\frac{\varepsilon}{\varepsilon_0} = 1 + \chi \quad \text{or} \quad (\because D = \varepsilon E)$$

$$\varepsilon_r = 1 + \chi \quad \text{or}$$

$$\boxed{\chi = \varepsilon_r - 1} \text{ --------- (2)}$$

POLARIZABILITY (α)

Dipole moment is directly proportional to the electric field intensity.

$$\mu \propto E \quad \text{or} \quad \mu = \alpha E \quad \text{where 'α' is polarizability of the medium}$$
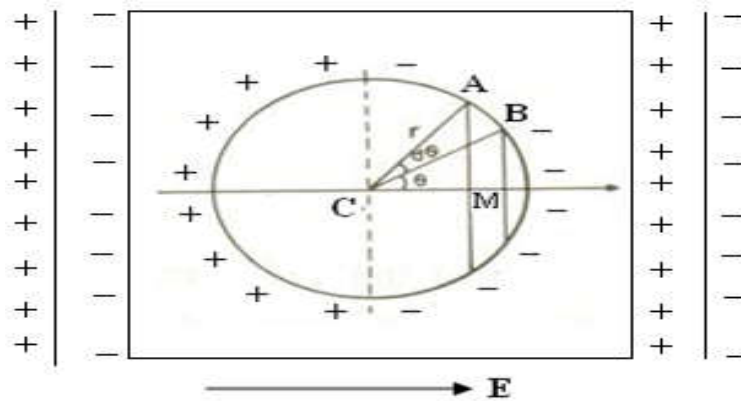
If medium possess 'N' molecules per unit volume, polarization

$$P = N\alpha E$$

INTERNAL FIELD OR LOCAL FIELD OF THE CUBIC DIELECTRICS

The electric field experienced by a dipole inside the dielectric medium is called local field or internal field E_{in}. It is different from the externally applied field.

Body of the dielectric between the condenser plates is shown in figure. We have to calculate the electric field experienced by a dipole at the center of the dielectric. Let us consider a spherical cavity with in the dielectric as shown in the figure. Polarized charges also appear on the surface of the sphere.

Consider a molecule of dielectric at the center 'C'of the dielectric. The dipole experiences the following fields in addition to the applied field.

$E_{in} = E_1 + E_2 + E_3 + E_4$

Where E_1 is electric field at center 'C' due to the charges on the surface of condenser plates.

E_2 is electric field at center 'C' due to the charges on the surface of the dielectric

E_3 is electric field at center 'C' due to the charges on the surface of the sphere

E_4 is electric field at center 'C' due to the permanent dipoles inside the sphere.

But in our present case, nonpolar, isotropic dielectric, it is zero. i.e. $E_4 = 0$

$\therefore E_{in} = E + E_3$ --------- (1)   ($\because E_1 + E_2 = E$, externally applied field)

Consider a small element of area 'ds' on the surface of the sphere making an angle 'dθ' with the center and 'θ' with the field direction. The polarization will be parallel to the electric field E.

The charge on the surface element is $q^1 = P\cos\theta\ ds$ ($\because p = \dfrac{q^1}{A}$, $p\cos\theta$ is parallel component of polarization)

Electric field intensity at center 'C' due to this charge is $dE_3 = \dfrac{1}{4\pi\varepsilon_0}\dfrac{q^1}{r^2}$

$$= \dfrac{1}{4\pi\varepsilon_0}\dfrac{p\cos\theta\ ds}{r^2} \qquad \text{-------- (2)}$$

Where 'r' is radius of the sphere. This field intensity is along 'r'. Therefore parallel component of the electric field E will be $dE_3 \cos\theta$

$$dE_3 = \frac{1}{4\pi\varepsilon_0} \frac{p\cos\theta\,ds}{r^2}\cos\theta \text{ --------- (3)}$$

The area of the small surface element is ds = $2\pi r(AB \times BM)$

From fig. $\sin\theta = \dfrac{BM}{r}$ or BM = $r\sin\theta$, $\sin d\theta = \dfrac{AB}{r}$ or $d\theta \approx \dfrac{AB}{r}$ or AB = $r\,d\theta$

$\therefore ds = 2\pi r^2 \sin\theta\,d\theta$

Substitute this value in equation (3), we get

$$dE_3 = \frac{P}{2\varepsilon_0}\cos^2\theta \sin\theta\,d\theta \text{ ----------- (4)}$$

Electric field intensity at 'C' due to the charges on whole sphere will be

$$E_3 = \frac{P}{2\varepsilon_0}\int_0^\pi \cos^2\theta \sin\theta\,d\theta$$

$$= \frac{P}{2\varepsilon_0}\cdot\frac{2}{3} \qquad (\because put \cos\theta = t, dz = -\sin\theta\,d\theta)$$

$$= \frac{P}{3\varepsilon_0}$$

$\therefore$ Total internal field $\boxed{E_{in} = E + \dfrac{P}{3\varepsilon_0}}$ --------- (5)

CLAUSIUS-MOSSOTTI EQUATION:

This equation gives the relation between the dielectric constant ε_r and polarizability α

We know $\chi = \varepsilon_r - 1$ or

$$\frac{P}{\varepsilon_0 E} = \varepsilon_r - 1$$

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

Internal field $E_{in} = E + \dfrac{P}{3\varepsilon_0}$

Substitute the 'P' value from equ.(1) in equ.(2)

$$E_{in} = E + \frac{\varepsilon_0(\varepsilon_r - 1)}{3\varepsilon_0}E$$

$$= E + \left[1 + \frac{\varepsilon_r - 1}{3} \right]$$

$$= E \, \frac{\varepsilon_r + 2}{3} \quad \text{--------- (2)}$$

Polarization is also proportional to the internal field E_{in}.

$$\therefore P = N\alpha \, E_{in} \text{ -------- (3)}$$

Where N is total no. of molecules in the dielectric, α is polarizability

$$\varepsilon_0(\varepsilon_r - 1) \, E = N\alpha \, \frac{\varepsilon_r + 2}{3} \, E \qquad \text{(from equ. (1) and (2))}$$

$$\boxed{\frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \frac{N\alpha}{3\varepsilon_0}} \text{ -------- (4) is called Clausius-Mossotti equation.}$$

Multiplying the above equation by $\dfrac{M}{\rho}$, where M is molecular weight and ρ is density.

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

$$\frac{\varepsilon_r - 1}{\varepsilon_r + 2} \, \frac{M}{\rho} = \frac{\alpha \, N_A}{3\varepsilon_0} \text{ ------- (5)} \qquad \left(\because number \ of \ molecules = \frac{N_A \, x \, density}{Molecular \, Weight} \right)$$

Where N_A is Avogadro's number $= 6.023 \times 10^{26}/kmol$

The quantity $\dfrac{\varepsilon_r - 1}{\varepsilon_r + 2} \, \dfrac{M}{\rho}$ is called molar polarization of a dielectric.
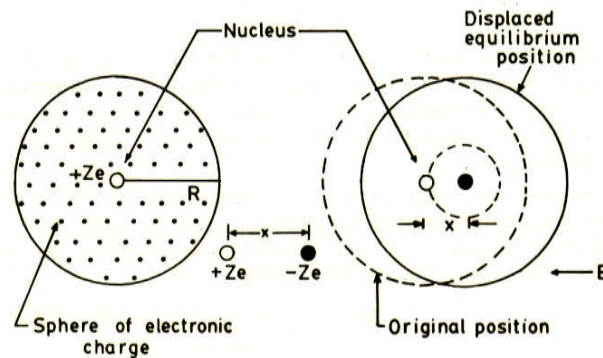
TYPES OF POLARIZATION:

Electronic Polarization

When an electric field is applied to the atom, electrons in the atom are displaced relative to the nucleus and produce dipole moment. Polarization arises due to the displacement of electron cloud relative to the nucleus, with in the same atom is called electronic polarization.

Electronic polarizability (α_e)

As shown in the figure +ze is charge of nucleus is surrounded by an electronic cloud of charge – ze distributed in a sphere of radius 'R'. Thus charge density of the electrons is *charge/volume,*

$$\rho = - \frac{ze}{\frac{4}{3}\pi R^3} = \left(-\frac{3}{4} \right) \frac{ze}{\pi R^3} \text{ -------- (1)}$$

When this system is subjected to an external field of intensity E, the nucleus and electron experiences a lorentz force of magnitude ZeE. Therefore electron and nucleus pulled apart opposite direction and a **coulomb attraction force** is developed between them. Let the displacement of electrons be 'x'.

Thus Lorentz force = -ZeE   and

Coulomb force = Ze x $\dfrac{1}{4\pi\varepsilon_0}$ $\left[\dfrac{ch\arg e\ enclosed\ in\ the\ sphere\ of\ radius\ x}{x^2} \right]$

The charge enclosed in the sphere of radius 'x' = charge density x volume (with radius x)

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

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

Hence coulomb force = Ze x $\dfrac{1}{4\pi\varepsilon_0 x^2}$ x $\left(-\dfrac{Zex^3}{R^3}\right) = -\dfrac{(ze)(ze)x}{4\pi\varepsilon_0 R^3}$

At thermal equilibrium the two forces are equal

i.e. $-ze\ E = -\dfrac{(ze)(ze)x}{4\pi\varepsilon_0 R^3}$ or $E = \dfrac{Ze\ x}{4\pi\varepsilon_0 R^3}$

$x = \dfrac{4\pi\varepsilon_0 R^3 E}{ze}$ This is expression for distance of separation between the two charges when electric field is applied.

$\therefore$ Dipole moment μ_e = charge x displacement
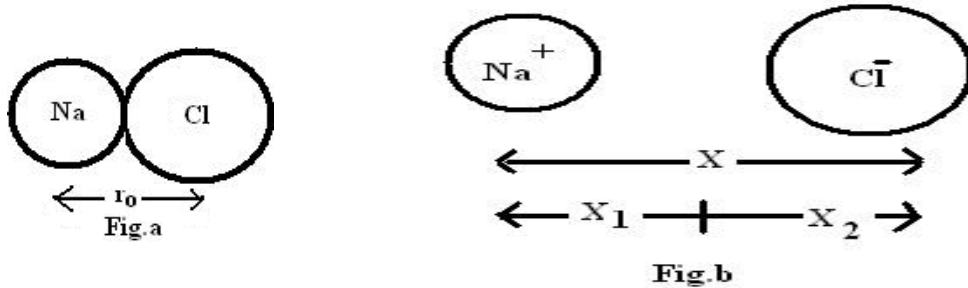
$$= ze\ x\ \frac{4\pi\varepsilon_0 R^3 E}{ze}$$

$$= 4\pi\varepsilon_0 R^3 E$$

$$= \alpha_e\ E$$

Where $\boxed{\alpha_e = 4\pi\varepsilon_0 R^3}$ is called electronic polarizability

Ionic Polarization:

Fig.a

Fig.b

This polarization occurs in ionic bonding compounds. When an electric field is applied positive and negative ions displace in opposite directions causing a change in length of ionic bond. This effect of change in length causes to dipole moment. So polarization arises due to relative displacement of ions is called ionic polarization.

Let us consider m and M are the masses of the positive and negative ions respectively. When electric field E is applied on an ionic dielectric then positive ions displace in the direction of the applied field through x_1 units of distance and negative ions displaced in opposite direction to the field through x_2 units of distance as shown fig.b

Hence net distance between two opposite ions $x = x_{1+}x_2$ ---- (1)
Lorentz force acting on the positive ion = eE ---- (2)
Lorentz force acting on the negative ion = eE ---- (3)

When ions are displaced in their respective directions from the mean positions, then the restoring force appears on the ions which tend to move the ions back to the mean positions.

∴ Restoring force acting on the positive ion = $k_1 x_1$ ---- (4) where k_1 force constant = $m\omega_0^2$
Restoring force acting on the negative ion = $k_2 x_2$ --- (5) where k_1 force constant = $M\omega_0^2$

At equilibrium position Lorentz force is equal and opposite to restoring force

Hence eE = $k_1 x_1$ or $x_1 = \dfrac{Ee}{m\omega_0^2}$ and $x_2 = \dfrac{Ee}{M\omega_0^2}$

From equation (1)

$x = x_{1+}x_2$

$$\therefore \quad x = \frac{Ee}{m\omega_0^2} + \frac{Ee}{M\omega_0^2}$$

$$= \frac{Ee}{\omega_0^2}[\frac{1}{m} + \frac{1}{M}]$$

But dipole moment μ = charge x displacement

$$= e\frac{Ee}{\omega_0^2}[\frac{1}{m} + \frac{1}{M}]$$

$$= \frac{Ee^2}{\omega_0^2}[\frac{1}{m} + \frac{1}{M}]$$
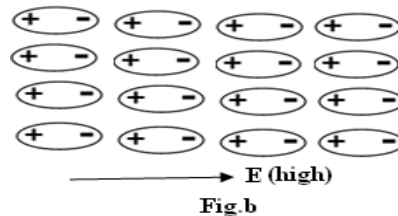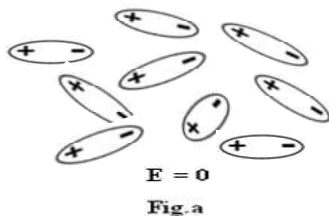
We know that ionic polarizability $\alpha_i = \frac{\mu}{E}$

$$= \frac{e^2}{\omega_0^2}[\frac{1}{m} + \frac{1}{M}]$$

Hence we can say that ionic polarizability is inversely proportional to square of the angular velocity ω_0 and reduced mass ($\frac{mM}{m+M}$).

Dipolar or Orientation Polarization:

This type of polarization only occurs in polar substances. In the absence of an external field the orientation of these dipoles is random. So that the net polarization is zero. When applied field is very strong these dipoles come to align. For ordinary fields these dipoles not

E = 0
Fig.a

E (high)
Fig.b

come to align completely because the orientation of dipoles is continuously disturbed by temperature.
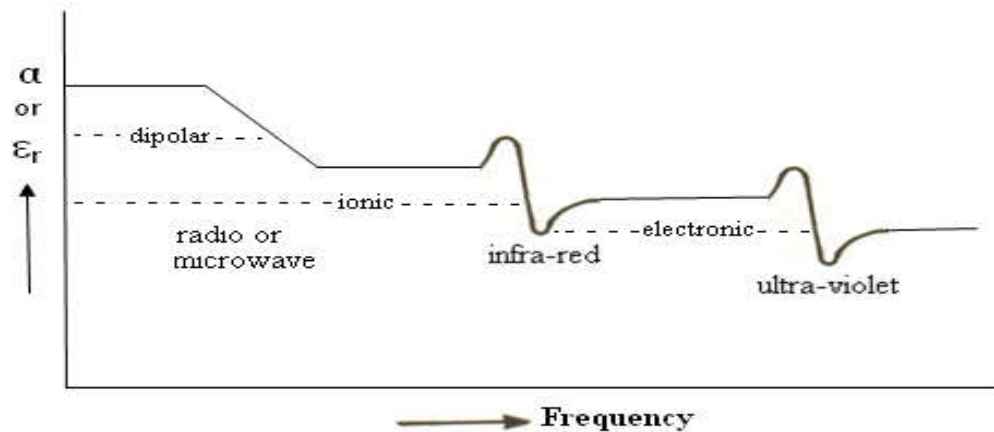
Anyway the dipole moment is induced when electric field is applied to polar molecules. This polarization is known as dipolar polarization. This polarization is strongly temperature dependent.

$$\text{Polarizability } \alpha_0 = \frac{\mu^2}{3K_BT}$$

where μ is the average dipole moment of all molecules.

FREQUENCY DEPENDENCE OF DIELECTRIC CONSTANT OR POLARIZABILITY:

Generally dielectrics are operated in alternating fields. When a dielectric is subjected to an alternating field, the components of polarizations (dipoles or electrons or ions) must follow the field reversals.

In audio frequency range i.e $<10^6$ Hz, all types of polarization are possible. The total polarizability $\alpha = \alpha_o + \alpha_i + \alpha_e$. (all types of polarizations are not exist in one material. This is for general case only for explanation).

Below this frequency the dipoles will get sufficient time to follow the field changes. Usually in the radio frequency region i.e. $10^6 - 10^{11}$ Hz, the permanent dipoles fail to follow the field reversals so dipolar or orientation polarization ceases in this region. As a result ε_r decreases considerably. The total polarizability is $\alpha = \alpha_i + \alpha_e$.
Usually in the infra-red region, i.e. 10^{11}-10^{14} Hz the positive and negative ions cannot follow the field variations. So ε_r decreases, ionic polarization ceases in this region. In this region only electronic polarization contributes to the total polarization. In the optical region the relative permittivity will be equal to square of the refractive index of dielectric i.e. $\varepsilon_r = n^2$.
In ultraviolet region, i.e. 10^{16}-10^{18} Hz the electron cloud also fails to follow the field alternations and electronic polarization ceases. Consequently the total polarization zero. Beyond the UV region, i.e. in x-ray frequency region, the relative permittivity of the medium tends to unity,$\varepsilon_r = 1$.

APPLICATIONS OF DIELECTRIC MATERIAL

Some of the applications of dielectrics are as follows-

- These are used for energy storage in capacitors.
- To enhance the performance of a semiconductor device, high permittivity dielectric materials are used.
- Dielectrics are used in Liquid Crystal Displays.
- Ceramic dielectric is used in Dielectric Resonator Oscillator.
- Barium Strontium Titanate thin films are dielectric which are used in microwave tunable devices providing high tunability and low leakage current.
- Parylene is used in industrial coatings acts as a barrier between the substrate and the external environment.
- In electrical transformers, mineral oils are used as a liquid dielectric and they assist in the cooling process.
- Castor oil is used in high-voltage capacitors to increase its capacitance value.
- Electrets, a specially processed dielectric material acts as electrostatic equivalent to magnets.

MAGNETISM AND DIELECTRICS

QUESTIONS

CHAPTER I

1. Define the terms permeability, susceptibility, magnetic flux density?
2. Define magnetic moment. Explain the origin of magnetic moment at the atomic level
3. Define magnetization and derive the relation between B,H and I
4. Explain the Classification of magnetic materials (Dia,Para ,Ferro,Anti ferro and Ferri)
5. Explain the Hysterisis loop (B or I-H Curve) observed in ferromagnetic materials ? What are hysteresis losses
6. Define Hard and soft magnetic materials
7. Discuss temperature dependence of susceptibility of para and ferromagnetic materials

CHAPTER II

1. What is meant by dielectrics? explain polar and non polar dieletrics
2. Define dielectric constant, electric polarization,electric susceptibility,Electric dipole, dipole moment ?
3. Define dielectric displacement and derive the relation between D, E and P
4. Define Clausius - Mosotti Relation in dieletrics
5. Explain electronic,ionic and orientational polarization and their dependence on temperature?
6. Define Dieletric loss and dielectric strength
7. Explain the hysteresis observed in ferroelectric materials?