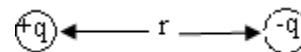# DIELECTRICS

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

μ_e = q x 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 (μ_e = q x 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'.

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

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

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:

1. Electric Field Intensity ($\bar{E}$) 2. Dielectric Polarization ($\bar{P}$) 3. Electric Displacement ($\bar{D}$)

1. 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 $\bar{F}$

2. 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),

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

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

3. 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

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the conducting surface. Let a charge 'q' be uniformly distributed on a conducting surface of area 'A',

$$D = \frac{q}{A} \ \ C/m^2 \ \ \text{or } q = D\,A.$$

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,

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

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

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

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

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

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

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

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$\varepsilon_r = 1+\chi$ or

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

Polarizability (α): Dipole moment is directly proportional to the electric field intensity.

$\mu \propto E$ or $\mu = \alpha E$ 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:

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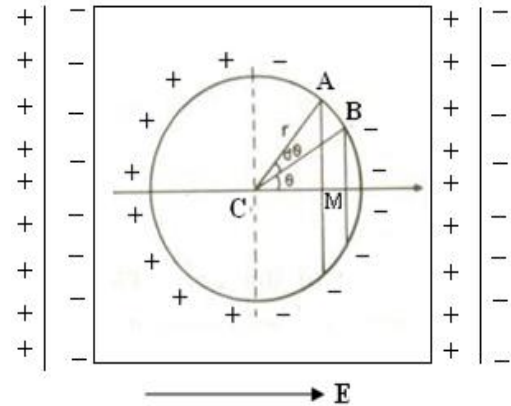
Consider a molecule of dielectric at the center 'C'of the dielectric. The dipole experiences the following fields in addition to the applied field.

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

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.

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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 $dE_3 = \dfrac{1}{4\pi\varepsilon_0} \dfrac{q^1}{r^2}$

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

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

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

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

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

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

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

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

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

$\therefore$ 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)

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

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

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

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.

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

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

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.

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TYPES OF POLARIZATION:

1. Electronic polarization   2. Ionic polarization   3. Dipolar or orientation 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,*
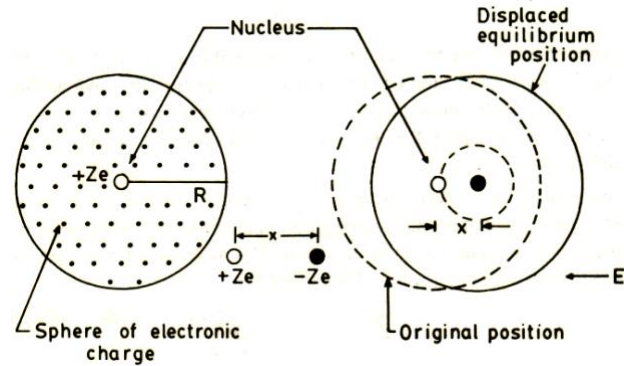
$$\rho = - \frac{ze}{\frac{4}{3}\pi R^3} = \left(-\frac{3}{4}\right)\frac{ze}{\pi R^3} \quad \text{-------- (1)}$$

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

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

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

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

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

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

At thermal equilibrium the two forces are equal

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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.

∴ Dipole moment μ_e = charge x displacement

$$= ze\ x\ \dfrac{4\pi\varepsilon_0 R^3 E}{ze}$$

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

$$= \alpha_e\ E$$

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

Ionic polarization:

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.

Fig.a

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

Fig.b
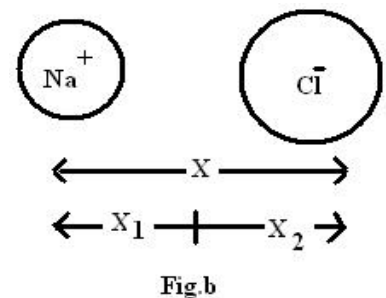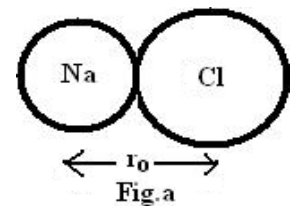
Hence net distance between two opposite ions $x = x_1 + x_2$ ---- (1)

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 $= M\omega_0^2$

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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)

$$x = x_{1} + x_{2}$$

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

$$= \dfrac{Ee}{\omega_0^2}\left[\dfrac{1}{m} + \dfrac{1}{M}\right]$$

But dipole moment μ = charge x displacement

$$= e\,\dfrac{Ee}{\omega_0^2}\left[\dfrac{1}{m} + \dfrac{1}{M}\right]$$

$$= \dfrac{Ee^{2}}{\omega_0^2}\left[\dfrac{1}{m} + \dfrac{1}{M}\right]$$

We know that ionic polarizability $\alpha_i = \dfrac{\mu}{E}$

$$= \dfrac{e^{2}}{\omega_0^2}\left[\dfrac{1}{m} + \dfrac{1}{M}\right]$$

Hence we can say that ionic polarizability is inversely proportional to square of the angular

velocity ω_0 and reduced mass $\left(\dfrac{mM}{m + M}\right)$.

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

come to align completely because the orientation of dipoles is continuously disturbed by temperature.

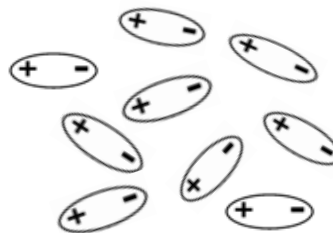Anyway the dipole moment is induced when electric field is
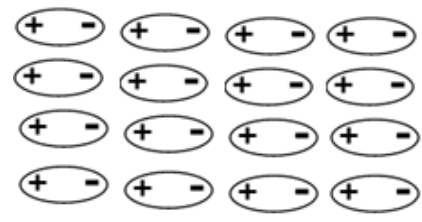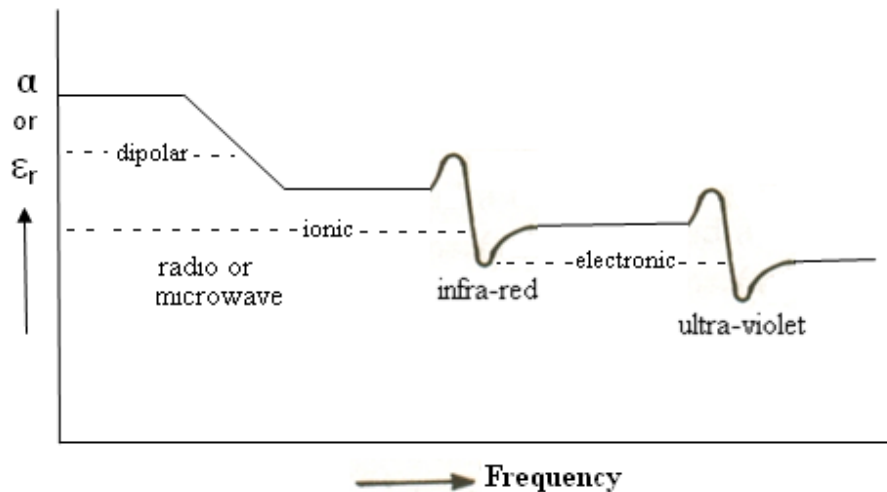

E = 0

Fig. a

E (high)

Fig. b

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applied to polar molecules. This polarization is known as dipolar polarization. This polarization is strongly temperature dependent.

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

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,$\varepsilon_r = 1$.

FERRO ELECTRICITY:

Definition: 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.
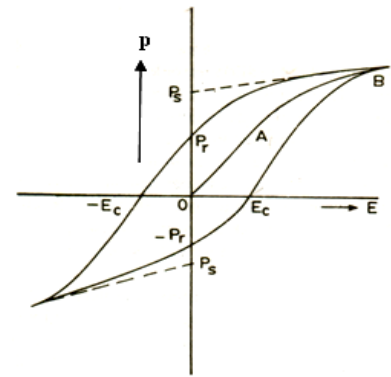
3. Ferro electrics exhibit hysteresis. When a virgin ferro electric crystal is subjected to an alternating electric field the polarization P increases nonlinearly with the applied field E and reaches saturation at a certain value of polarization. The polarization does not change even if E is further 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.

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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.
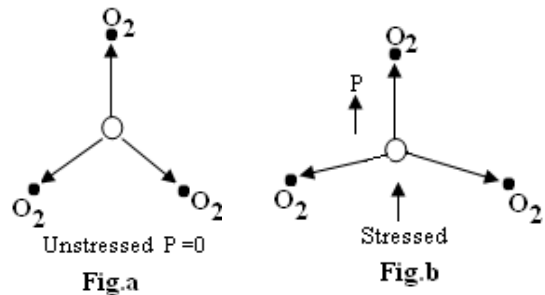
PIEZO ELECTRICITY:

Definition: Certain crystals exhibit polarization when they are subjected to external stress are called piezo electrics and this property is called piezo electricity.

Converse is also true. i.e. when electric field is applied, strain is produced in the crystal. Generally very large electric fields are needed to produce very small strains.

Examples: Quartz.

When stress is applied to piezo electric crystals, the ions in the material are displaced the original charge distribution and causes increase in dipole moment as shown in figure (b).

Piezo electricity in Quartz crystal:

Unstressed P =0
Fig.a

Stressed
Fig.b
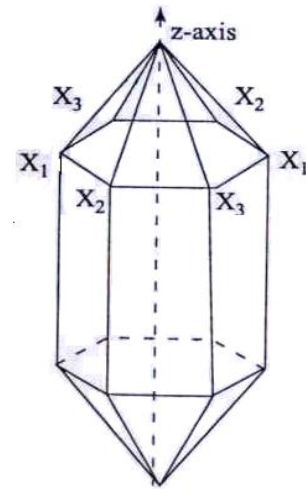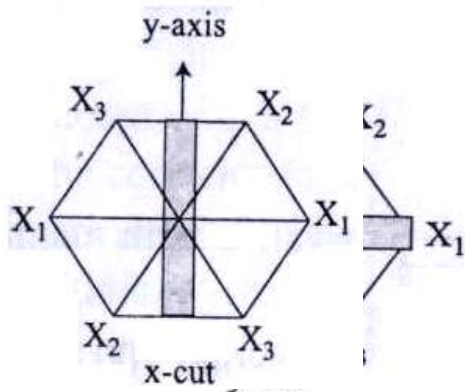
Natural quartz crystal has the shape of hexagonal prism with a pyramid attached to each end.Fig.a shows the shape of the quartz crystal, the line joining the apex points of pyramids is called *optical axis or z-axis.* Optic axis has three fold symmetry. The three lines joining opposite corners are called *electrical axes or x-axes.* Similarly the three lines which are joining opposite sides constitute *mechanical axes or y-axes.*

The three electrical and mechanical axes are at right angles to the optic axis and at 120^0 to each other. Thin plates of quartz crystal cut perpendicular to one of its x-axis are known as x-cut planes. Similarly, thin plates of the crystal cut perpendicular to one of its y-axis are known are y-cut planes.

Let us consider an x-cut crystal plate. Let its thickness be 't' and length 'l'. If an alternating voltage is applied to the crystal plate, alternating stresses and strains are set up both in its thickness and length. The frequency of the thickness vibrations is given by

$$f = \frac{m}{2t}\left[\frac{Y}{\rho}\right]^{1/2} \text{ --------- (1)}$$

and frequency of the length vibration is given by

$$f = \frac{m}{2l}\left[\frac{Y}{\rho}\right]^{1/2} \text{ --------- (2)}$$

where m = 1, 2, 3……etc. stand for fundamental, first overtone, second overtone…… respectively

Y is young's modulus and ρ the density of the crystal plate.

Applications:

1. Piezo electric crystals are used as transducers i.e.to convert electrical energy into mechanical energy and vice versa.

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2. Piezo electric crystals are used in gram phone and guitar pick ups.

3. They are used to generate and detect SONAR waves.

4. They are used to generate high voltage and power sources.

5. Piezo electric sensors especially used in ultrasonic transducers for medical imaging and nondestructive testing (NDT)

DIELECTRIC BREAKDOWN:

When a dielectric loses its insulation and allows large current to pass through it, it is said to be breakdown.

The important types of dielectric breakdowns are

1. Intrinsic breakdown   2. Thermal breakdown   3. Electro chemical breakdown

Intrinsic Breakdown:

In perfect dielectrics there are no free electrons and conductivity is almost zero. In a pure dielectric the valence band is separated from the conduction band by very large energy gap, the electrons cannot jump to the conduction band. To remove an electron from the atom the field of order of 10^8 V/cm is required. *Thus electrons move from the valence band to the conduction band is called intrinsic breakdown.*

Characteristics:

1. This can occur even at low temperatures

2. This requires relatively large electric fields

3. Mostly this kind of breakdown occurs in thin samples

4. This does not depend on the electrodes and shape of the sample

Thermal Breakdown:

The electrical energy loss has to be dissipated as heat and if the rate of heat generation in a dielectric exceeds the rate of dissipation, current will flow through the material and immediately dielectric breakdown occur.

Characteristics:

1. This can occur only at high temperatures

2. The strength of electric field to create dielectric breakdown depends upon the material size and shape

3. The breakdown strength is lower for ac voltages than dc voltages

Electro Chemical Breakdown:

Chemical and electro chemical breakdown have a close relationship with thermal breakdown. When temperature rises, mobility of ions increases and hence electro chemical reaction takes place. When ionic mobility increases leakage current also increases and this will lead to dielectric breakdown.

Not only by the application of electric field but also so many ways the chemical reaction occurs.

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a) Some materials oxidize in presence of air or ozone. Particularly if we take rubber it is converted into oxide in air and cracks are produced in it in ozone atmosphere.

b) Due to moisture and temperature the electrical and mechanical properties of cellulose esters are decreasing gradually.

c) when foreign materials are joined with insulating materials, the insulating properties of them are reduced due to some chemical reactions.

To avoid electro chemical reactions:

1. the impurities should be avoided in the insulating materials

2. It should not be operated at high temperatures

3. If the insulating material is polar it has some permanent dipoles which give large leakage current leads to breakdown. Therefore polar compounds should not be used at high temperature.

ACTIVE AND PASSIVE DIELECTRICS:

Active dielectrics are the electric filed generators which are also called non linear dielectrics.

Ex: Ferro electrics.

Passive dielectrics are acts as insulating materials and absorb electric field energy which are also called linear dielectrics.

Ex: general dielectrics.

P.Srinivasarao

MAGNETIC PROPERTIES

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 (τ): 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 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.

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.

Def: 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 $\quad I = \dfrac{Induced\, magnetic\, moment}{Volume}$

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

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

$B \propto H$

$B = \mu H$

Where µ permeability of medium

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

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.

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

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 = $\mu_0 I$

$$B = \mu_0 [H+M] \text{ --------(1)}$$

This is the relation between B, H and I.

Divide the above equation by H, we get

$$\frac{B}{H} = \mu_0 [1 + \frac{M}{H}]$$

$$\mu = \mu_0 (1 + \chi)$$

$$\frac{\mu}{\mu_0} = 1 + \chi$$

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

ORIGIN OF MAGNETIC MOMENT:

In general the magnetic moment of atom originate from 3 sources:

1) orbital motion of electrons

2) spin motion of electrons

3) nuclear spin

ORBITAL MOTION OF ELECTRONS: BHOR 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 revolving around the positive nucleus. The magnetic moment possessed by an electron which is revolving around the nucleus is given by

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

Where I is current in the circular loop of orbit. A, area enclosed by the circulating current.
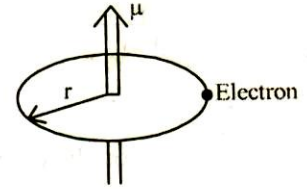
We know $I = \dfrac{ev}{2\pi r}$, r is the radius of the circular orbit   (I = q/t, t = distance/speed)

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 $l = 0, 1, 2\ldots$ (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 $\dfrac{lh}{2\pi}$

$$\therefore \ \mu_m = -\left(\dfrac{e}{2m}\right)\dfrac{lh}{2\pi}$$

$$= -\left(\dfrac{eh}{4\pi m}\right)l$$

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$$= -\mu_B. \, l \text{ -------- (4)}$$

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 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 dia magnetic.

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

Nuclear Spin: - The magnetic moment of the nucleus is given by

$$\mu_{ps} = \frac{eh}{4\pi M_p} = 5.05 \times 10^{-27} \text{ A-m}^2 \quad \text{where } M_p \text{ represents the mass of proton}$$

which is nearly 1/2000 as much as that of an electron.

$\therefore$ 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.

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.

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)
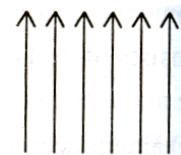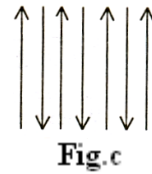

Fig.b

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. And their spin orientations as shown in fig.(c).

Fig.c

Ferri magnetic: If the neighbouring dipoles are orient anti parallel and the with unequal magnitudes, the materials are called ferri magnetic and their orientation is shown in fig.(d)

Fig.d
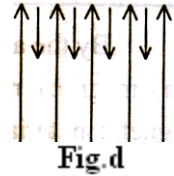
DIAMAGNETIC MATERIALS:

The materials which are magnetized in the direction opposite to the magnetic field are called diamagnetic materials. or

The materials which can not be magnetized in the external magnetic field are called diamagnetic materials.

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

The salient features are:

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

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

3. 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

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

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

6. when the diamagnetic substance is placed in nonuniform magnetic field, it move towards the weaker region of the field.
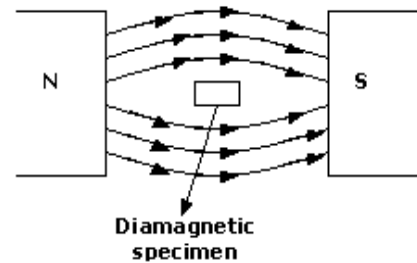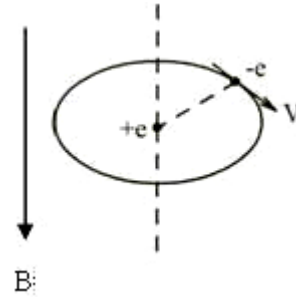
LANZEVIN'S THEORY OF DIAMAGNETISM : *Susceptibility of diamagnetic materials*

When an electron is revolving in circular orbit, orbit acts as current loop. This current loop produces magnetic moment μ which is opposite to the direction of the field.

Let ω_0 be the angular velocity of the electron. The magnitude of the magnetic moment μ is given by

$$\mu = I \times A \text{ --------- (1)}$$

$$= \frac{ev}{2\pi r} \times \pi r^2$$

$$= -\frac{e\omega_0}{2\pi} \times \pi r^2 \qquad \qquad [\omega_0 = \frac{v}{r}]$$

$$= -\frac{1}{2} e\omega_0 r^2 \text{ -------- (2)}$$

According to Lenz's law electric field setup in the circular orbit

$$\oint E.dl = -\frac{d\phi}{dt}$$

$$E.2\pi r = -\frac{d\phi}{dt}$$

$$E = -\frac{1}{2\pi r} \frac{d\phi}{dt} \text{ ---------- (3)}$$

We know $B = \frac{\phi}{A}$ or $\phi = B \times A$

$$E = -\frac{1}{2\pi r} \frac{dB}{dt} \pi r^2$$

$$E = -\frac{r}{2} \frac{dB}{dt} \text{ --------- (4)}$$

We know F = ma = -eE or

$$ma = \frac{er}{2} \frac{dB}{dt} \text{ or}$$

$$a = \frac{er}{2m} \frac{dB}{dt}$$

$$dv = \frac{er}{2m}\frac{dB}{dt}dt \quad \text{or}$$

$$= \frac{er}{2m}dB \text{---------(5)}$$

∴ The change in the angular velocity $d\omega = \frac{dv}{r} = \frac{e}{2m}dB$

$$\int_{\omega_0}^{\omega} d\varpi = \omega - \omega_0 = \frac{e}{2m}B$$

$$\therefore \omega = \frac{e}{2m}B \text{----------(6)} \quad \text{This is increase in the angular velocity of the electron when}$$
magnetic field is applied to the atom.

The term $\frac{e}{2m}B$ is called Larmour's frequency.

∴From equ. (2) $\mu = -\frac{1}{2}e\omega_0 r^2$

The change in magnetic moment $d\mu = -\frac{e^2 r^2 B}{4m}$ ---------(7)

For spherically symmetric atom r_x, r_y, r_z be the average radii for all the electrons along the three axes then

$$r_0^2 = r_x^2 + r_y^2 + r_z^2 \quad \text{and}$$

$$r_x^2 = r_y^2 = r_z^2 = \frac{r_0^2}{3}$$

for x and y axes $r^2 = r_x^2 + r_y^2 = \frac{r_0^2}{3} + \frac{r_0^2}{3} = \frac{2r_0^2}{3}$ --------(8)

∴ from equ.s (7) and (8) , we get $d\mu = -\frac{2e^2 r_0^2 \mu_0 H}{12m}$

If material contains N number of atoms per unit volume,

$$\chi_{\text{dia}} = -NZ\left[\frac{e^2 r^2 \mu_0}{6m}\right] \text{----------(9)} \quad \left(\because \chi = \frac{Induced\ magnetic moment}{volume}\right)$$

where z is atomic number, μ_0 is permeability of air or free space
For diamagnetic materials the susceptibility is of the order of 10^{-6}.

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.

The properties are as follows:

1. paramagnetic materials exhibit +ve magnetic susceptibility, the susceptibility is of the order of 10^{-6}

2. The relative permeability μ_r is slightly more than unity.

3. 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

4. The paramagnetic susceptibility is strong dependent on temperature. The susceptibility is inversely proportional to temperature. Thus

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

5. The magnetization M varies linearly with the applied field when the field is not too strong.

6. In no uniform field the paramagnetic substances are attracted towards stronger region of magnetic field.

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.

The properties are:

1. Ferro magnetic materials exhibit very high values of magnetic susceptibility and relative permeability. Susceptibilities ae of the order of 10^6 and relative permeabilities are of the order of a few thousands.

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

3. As the temperature increases susceptibility decreases, above a certain temperature ferro magnetic material become ordinary paramagnetic and this temperature is called curie temperature.
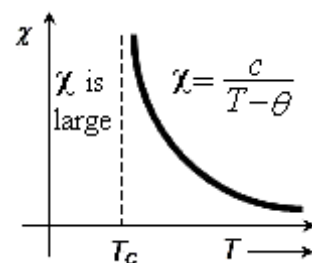
Susceptibility follows the curie's law. $\chi = \dfrac{c}{T-\theta}$, where θ is paramagnetic curie's temperature.

For $T > \theta$ material transforms into paramagnetic state, $T < \theta$ material is in ferromagnetic state.

4. 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.
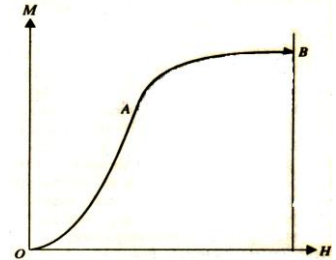

5. Ferro magnetic material exhibit hysteresis.

When the ferromagnetic material is placed in magnetic field, magnetization increase first slowly, then more rapidly and finally attains a saturation value. Above the saturation value B or M does not vary with increase of H.

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. To bring back the magnetization zero the magnetic field is applied in reverse direction which is called coercive field H_c.

As the field increased in negative direction saturation is ultimately reached in reverse direction. Now the field is increased a closed loop is obtained called hysteresis loop. When the magnetic field is applied in reverse direction,

some magnetic energy is lost in the form of heat. This is known as hysteresis loss which is equal to the area of the hysteresis loop.
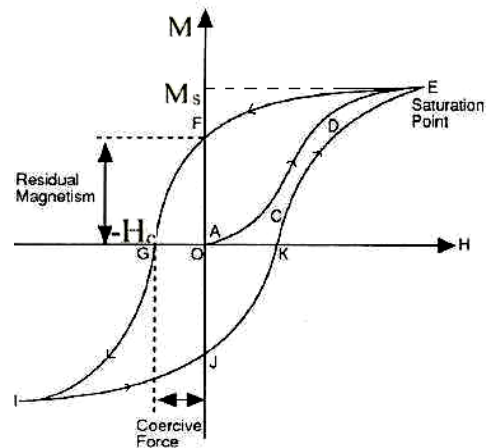
DOMAIN HYPOTHESIS:

In order to explain why virgin sample of ferro magnetic material has no magnetic moment, Weiss postulated that *entire ferromagnetic material split into a large no. of small regions of spontaneous magnetization. These regions are called domains.*

Every domain having a definite value and direction of the magnetic moment. 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.
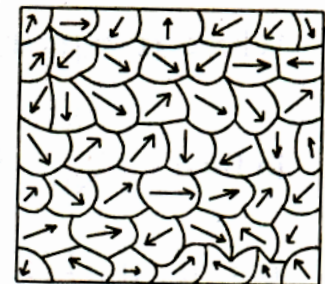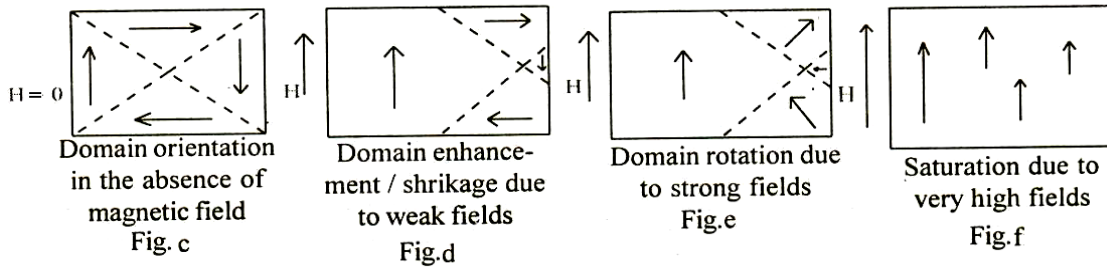

Fig. Ferromagnetic domains

Domain orientation
in the absence of
magnetic field
Fig. c

Domain enhance-
ment / shrikage due
to weak fields
Fig.d

Domain rotation due
to strong fields
Fig.e

Saturation due to
very high fields
Fig.f

In fig.(c) domain arrangement for zero resultant magnetic moment is shown. If external magnetic field is applied to ferromagnetic specimen two things can happen, according to domain model.

i) the domains parallel or nearly parallel to the filed direction H, can grow in size as shown in fig.(d)

ii) The magnetic moment of the domains can rotate in to the field direction is shown in fig.f

HYSTERESIS ON THE BASIS OF DOMAIN THEORY:

Domain theory use to explain the hysteresis of ferro magnetic material.

In the absence of magnetic field the domains in the material are randomly oriented and the resultant magnetic moment is equal to zero. When a small magnetic field is applied domains which are parallel or almost parallel to the field, can grow in size. As a result a large increase in magnetization which is shown in figure.
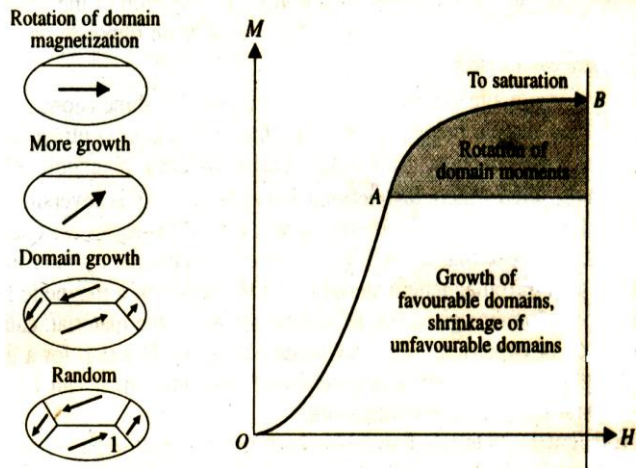
Further increase in field the magnetization vector of domain rotates and comes along the field direction. Here magnetization increases slowly and finally attain a saturation which is shown in fig. On decreasing the field, magnetization dons not follow the original path. Because the aligned domains do not regain their random state of orientation easily. When applied field is zero there exists some non zero magnetization. This magnetization I s called residual magnetization or retentivity. To bring back magnetization to zero a reverse magnetic field is applied which is called coercive field. When coercive field is applied some work is done on the specimen. This work done is converted in to heat energy. This is called hysteresis loss.

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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) $H_{eff.} = H + H_i$

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

Where H is applied field and γ is called molecular field constant which is also known as Weiss constant.

According to Weiss every Ferro magnetic substance should initially exhibit paramagnetism.

$\therefore$ Susceptibility of paramagnetism $\chi = \dfrac{M}{H} = \dfrac{c}{T}$

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

$$\chi = \dfrac{M}{H + \gamma M} = \dfrac{c}{T}$$

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

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

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

Where $\theta = \gamma c$. From equ.(2) it is clear that magnetization tends to infinity at $T = \theta$. It means that the interaction of the individual magnetic moments reinforce each other causing them to align parallel at $T = \theta$. Equation (1) suggests that nonvanishing magnetization for $T = \theta$ even in the absence of magnetic filed.

When H = 0, the magnetic dipoles are subjected only to the molecular field H_i.

$\therefore$ from the Langevin's variable, $\beta = \dfrac{\mu_m H_i}{K_B T} = \dfrac{\mu_m \gamma M}{K_B T}$ or

$$M = \dfrac{K_B T \beta}{\gamma \mu_m} \text{---------- (3)}$$ where μ_m is magnetic moment of

each dipole and M is magnetization.

From the above equation M varies linearly with β. M also given by the expression

$$M = N\mu_m \left[\cot h\beta - \frac{1}{\beta} \right] \text{-----------(4) \quad or}$$

$$M = N\mu_m L(\beta) \quad \text{where} \quad L(\beta) = \left[\cot h\beta - \frac{1}{\beta} \right]$$

Equation (3) and (4) are simultaneous equations, spontaneous magnetization will occur if there exist a solution for equations (3) and (4).

Since 'M' must satisfy both (3) and (4), its value at a given temperature may be obtained from the point of intersection of two curves of 'M' versus 'a' shown in figure (a).

Equation (4) gives curve, equation (3) gives straight line with different values of temperature T.
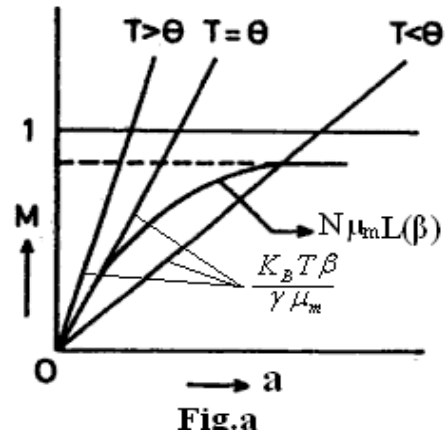
Fig.a

From the fig.a,

(i) Straight line for which T< θ (θ is ferromagnetic curie temp.) intersects the curve due to equ.(4) at non zero value which means there is some magnetization M although the external field is zero.

∴ For T < θ, material exhibit spontaneous magnetization.

(ii) The line T = θ represents tangent to the curve at the origin at which M = 0. This means there will be no spontaneous magnetization when T = θ. So θ is called ferromagnetic curie's temperature above which the spontaneous magnetization vanishes.

(iii) The line T > θ does not interact with the curve, therefore spontaneous magnetization cannot arise.

FERRIMAGNETIC MATERIALS (FERRITES):

If the magnetic moments of sub lattice in a crystal are unequal in magnitude but opposite in direction are called ferromagnetic materials and exhibit most of the properties of ferromagnetism and the crystals which exhibit this property are called *ferrites*.

All compounds of mixed oxides of metals exhibit ferrimagnetism. The chemical formula is
MeO Fe_2O_3. Where Me is a divalent ion like Barium, strontium, Zinc, Cadmium, Magnesium and Nickel etc.,

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Characteristics:

1. Ferrites exhibits non linear magnetization curve.

2. Ferrites exhibit spontaneous magnetization below curie temperature

3. They exhibit hysteresis loop.

4. Ferrites processes high permeability values normally

5. Ferrites are good insulators. They are not metals, they are ionic compounds.

APPLICATIONS OF FERRITES:

1 *Ferrites used as switch:*

  In Ni-Zn ferrite the permeability drops to zero sharply near the curie temperature. This property
  is used in thermal sensing switches which are used in refrigerators, air   conditioners etc.,

2. *Production of Ultrasonic Waves*:

  Ferrites exhibit magnetostriction. when ferrite rod is kept in varying magnetic field it vibrates.
  This phenomenon is used in production of ultrasonic waves of KHz frequency range.

3. *Ferrites are core materials:*

  Ferrites are used as cores of transformers. As the losses are low in ferrites, they improve the
  selectivity and sensitivity of radio receivers

4. *In digital computers:*

  Ferrites are used as bistable elements, shift registers in digital computers

5. *Harmonic generation:*

  Using non linear permeability property, ferrites can be used in devices power limiting
  and harmonic generation.

6.*Electromagentic Interference Suppression:* Using ferrites in electronic equipment unwanted
high frequency signals can be blocked, wanted signals can be allowed.
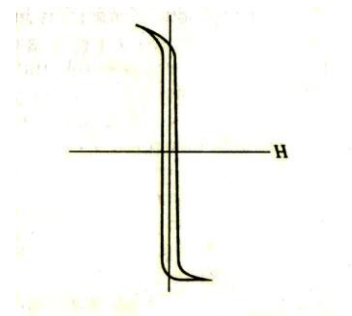
SOFT AND HARD MAGNETIC MATERIALS:

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.

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

2. These materials having large values of permeability and susceptibility

3. Coercivity and retentivity are small.

4. These materials are free from irregularities

5. Its magneto static energy is small.

6. 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:

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

2. These materials have small values of permeability and susceptibility.

3. Coercivity and retentivity are high.

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

5. Its magneto static energy is more

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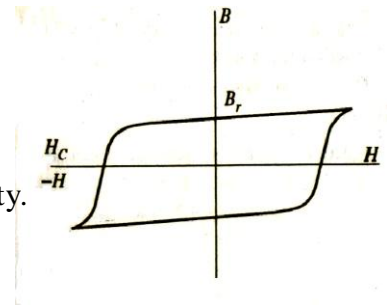
Examples: Al-Ni-Co alloy, Cu-Ni-Co alloy*P.*

p.srinivasarao