

Unit – III

MAGNETIC AND DIELECTRIC PROPERTIES OF MATERIALS

DIELECTRIC PROPERTIES OF MATERIALS

3.8 Dielectric loss

When an AC field is applied to a dielectric material, some amount of electrical energy is absorbed by the dielectric material and remaining amount of energy is losses in the form of heat. This loss of energy is known as dielectric loss.

Dielectric loss can occur in both direct and alternating voltages. It is less in direct voltage than that of alternating voltages.

Loss in ideal dielectric

If an alternating voltage is applied across the ideal dielectric, the charging current (I) leads the voltage by an angle of 90° as shown in figure.

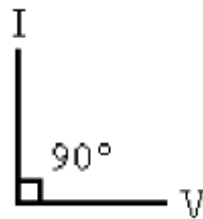


Fig 3.8.1.Variation of current with voltage

We know that,

$$\text{Power loss } P_L = VI \cos \theta$$

$$\theta = 90^\circ$$

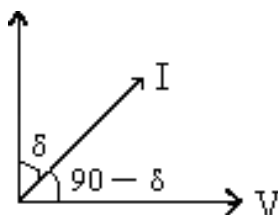
$$P_L = VI \cos 90^\circ$$

$$P_L = 0 [\cos 90^\circ = 0]$$

This means that no electrical energy is lost during charging.

Loss in commercial dielectric

In a practical dielectric, the current leads the voltage by $(90 - \delta)$. This shows that there is some loss in electrical energy as shown in figure.



δ – Dielectric loss angle

This loss angle is a measure of the power dissipated in each cycle. The power loss for a dielectric having a capacitance and a voltage V applied to it at a frequency F is given by

$$\text{Power loss } P_L = VI \cos \theta$$

$$\text{Since } \theta = 90 - \delta$$

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

$$P_L = VI \sin \delta \dots \dots \dots (1)$$

We know that

$$V = IR$$

$$I = \frac{V}{R}$$

Substitute equation (2) in (1) we get,

$$\text{Power loss } P_L = VI \cos \vartheta (90 - \delta)$$

$$P_L = \frac{V^2}{R} \sin \delta \dots \dots \dots (3)$$

We know that

$$\text{Frequency } f = \frac{1}{2\pi f c}$$

Therefore

$$R = \frac{1}{2\pi f c}$$

Substituting equation (4) in (3)

$$\text{Power loss } P_L = 2 \pi f C V^2 \sin \delta$$

If δ is very small, then $\sin \delta = \tan \delta$

Therefore

$$\text{Power loss } P_L = 2 \pi f C V^2 \tan \delta$$

Hence $\tan \delta$ is called the power factor of dielectric. If f, C, and V are constants then

$$P_L \propto \tan \delta \dots \dots \dots (5)$$

The power loss depends only on the power factor of the dielectric as long as the applied voltage, frequency and capacitance are kept constant. Naturally, power loss varies with frequency.

3.9 Dielectric breakdown

When a dielectric is placed in an electric field and when the field exceeds the critical field, the dielectric loses its insulation property and becomes conduction. This phenomenon is known as dielectric breakdown.

Dielectric strength

The electrical field strength at which dielectric breakdown occurs is known as dielectric strength. It is the breakdown voltage per unit thickness of the material

$$\text{The dielectric strength} = \frac{\text{Dielectric voltage}}{\text{thickness of dielectric}}$$

There are different mechanisms by which the dielectric breakdown takes place. Some of the types of breakdown are

1. Intrinsic (or) avalanche breakdown
2. Thermal breakdown
3. Chemical and electrochemical breakdown
4. Discharge breakdown
5. Defect breakdown

3.9.1 Intrinsic (or) avalanche breakdown

When a dielectric is subjected to electric field then the electrons in the valence band acquire sufficient energy, go to conduction band by crossing the energy gap, and hence become conducting electrons. Therefore, large current flows and is called Intrinsic (or) Zener breakdown

Avalanche breakdown

These conduction electrons on further application of field collide with the valence electrons, which are involved in the covalent bonds and remove more electrons hence transferring them as conduction electrons. This process continues as a chain reaction. Therefore, very large current flows through the dielectric and hence called avalanche breakdown

Characteristics

1. It can occur even at lower temperatures
2. It requires relatively large electric fields
3. This kind of breakdowns occurs in thin samples
4. It does not depend on the electrodes and shape of the material.
5. It occurs within a short span of time (milliseconds)

3.9.2 Thermal Breakdown

When a dielectric is subjected to an electrical field, heat is generated. The generated heat is dissipated by the dielectric. In some cases, the heat generated will be very high compared to the heat dissipated. Under such conditions, the temperature inside the dielectric increases which results in local melting. Once melting starts, that particular region becomes highly conduction. So enormous current flows through the material and dielectric breakdown occurs

Characteristics

1. It can occur even at higher temperatures
2. It requires moderate electric fields
3. It depends on the size and shape of the dielectric material
4. Since the dielectric loss is proportional to frequency, the breakdown occurs at relatively lower field strength
5. It occurs in the order of milli seconds

3.9.3 Chemical and electrochemical breakdown

This type of breakdown is almost similar to the thermal breakdown. If the temperature increases, mobility of the ions will increase. When mobility increases, leakage current also increases and hence the electro chemical reaction may be induced to take place.

Therefore when mobility of ions is increased, insulation resistance decreases and hence dielectrics become conducting. This type of break down is known as Chemical and electrochemical breakdown

Characteristics

1. It can occurs only at lower temperatures
2. It occurs even in the absence of electric field
3. It depends on the concentration of ions and magnitude of leakage curr4ent

3.9.4 Discharge breakdown

In some dielectric gas bubbles are present. When these dielectrics are subjected to electric field, the gas present in the material will easily ionize and hence produce large ionization current and is known as Discharge breakdown

Characteristics

1. It occurs at low voltages

2. It occurs due to the presence of gas bubbles
3. It depends upon the frequency of the applied voltage

3.9.5 Defect breakdown

Some dielectrics have defects such as cracks, pores, blow holes etc. These vacant position may have moisture or impurities which leads too breakdown known as defect breakdown

3.9.6 Remedies for breakdown mechanisms

To avoid breakdown the dielectrics should have the following properties

- (i) It should possess high dielectric strength
- (ii) It should have high resistivity
- (iii) Dielectric loss should be low
- (iv) Thermal expansion should be low
- (v) It should have sufficient mechanical strength
- (vi) It should be fire proof
- (vii) It must have less density
- (viii) It should be resistive to oils, liquids and gases
- (ix) There should not be any defects
- (x) It must be in pure form

UNIT-III

MAGNETIC AND ELECTRICAL PROPERTIES OF MATERIALS

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3.6. Domain Theory of Ferro Magnetism

3.6.1 Energies involved in the domain growth (or) Origin of Domain theory of Ferromagnetism

3.6. Domain Theory of Ferro Magnetism

This theory was proposed by Weiss in 1907. It explains the hysteresis and the properties of ferromagnetic materials.

Postulates of domain theory:

1. A ferromagnetic material is divided into a large number of small region called domains (0.1 to 1 of area)
2. In each domain the magnetic moments are in same direction.
3. But the magnetic moment varies from domain to domain and the net magnetization is zero,
4. In the absence external magnetic field all the magnetic moments are in different direction.
5. When a magnetic field is applied there are two process takes place
 - ❖ By the motion of domain walls.
 - ❖ By the rotation of domains.

By the motion of Domain walls

When a small amount of magnetic field is applied, the dipoles in the domains are aligned parallel to the applied magnetic field. It increases domain area by the motion of domain walls.

By the rotation of Domains

If the applied magnetic field is further increased, the domains are rotated parallel to the field direction by the rotation of domains.

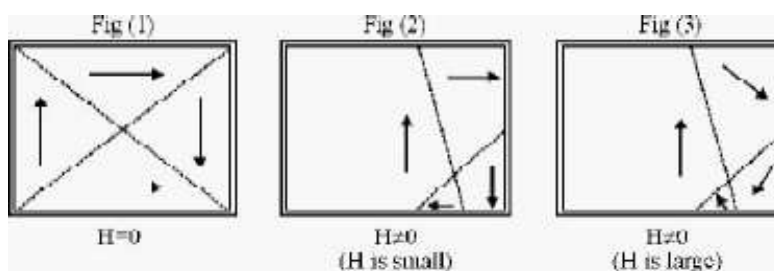


Fig 3.6.1.Effect of magnetic field

3.6.1 Energies involved in the domain growth (or) Origin of Domain theory of Ferromagnetism

The total internal energy of the domain structure in a ferromagnetic material is made up from the following

1. Exchange energy (or) Magnetic field energy.
2. Crystalline energy (or) Anisotropy energy.
3. Domain wall energy (or) Bloch wall energy.
4. Magnetostriction energy

1. Exchange energy (or) Magnetic Field energy

“The interaction energy which makes the adjacent dipoles align themselves” is the called **exchange energy (or) magnetic field energy**. It arises from an interaction of electron spins. It depends upon the inter atomic distance. This exchange energy also called magnetic field energy.

Whose energy is required in assembling the magnets into a single domain and this work done is as potential energy. The volume of the domain may be between 10^{-2} to 10^{-6} cm³.

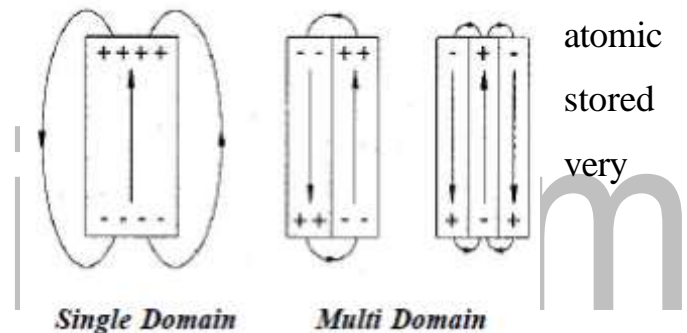


Fig 3.6.2 Exchange energy

2. Anisotropy energy

The excess of energy is required to magnetize a specimen along the hard direction is called the crystalline anisotropy energy. In ferromagnetic materials there are two types of directions of magnetization namely,

- ❖ **Easy direction and**
- ❖ **Hard directions.**

In easy direction of magnetization, weak field can be applied and in hard direction of magnetization, strong field should be applied.

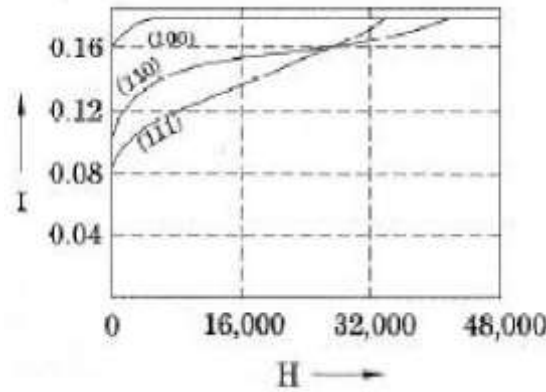


Fig 3.6.3.Direction of magnetization

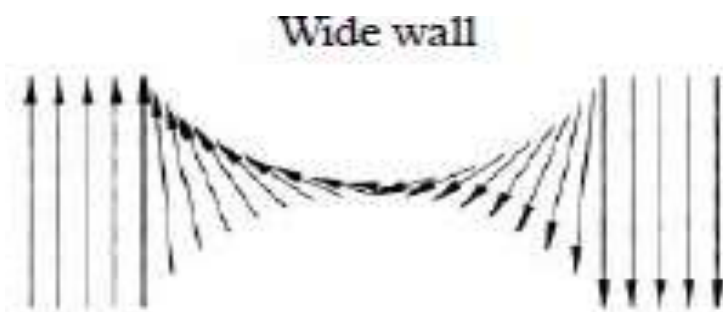
Crystalline anisotropy energy

The energy of magnetization which is the function of crystal orientation. As shown in figure magnetization curves for iron with the applied field along different crystallographic direction crystallographic directions have been drawn. For example, in BCC iron the easy direction is [100], the medium direction is [110], and the hard direction [111]. This energy is very important in determining the characteristic domain boundaries.

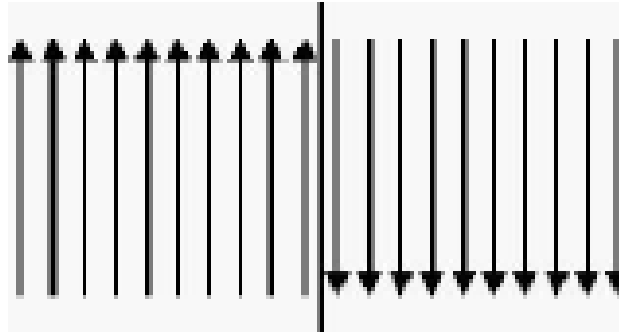
3. Domain wall energy or Bloch wall energy

A thin boundary or region that separates adjacent domains in different directions is called domain wall or Bloch wall. The size of the Bloch walls is about 200 to 300 lattice constant thickness. The energy of domain wall is due to both exchange energy and anisotropic energy. Based on the spin alignments, two types of Bloch walls may arise, namely

Thick wall: When the spins at the boundary are misaligned and if the direction of the **spin changes gradually** as shown in below figure, it leads to a thick Bloch wall. Here the misalignments of spins are associated with exchange energy.



Thin wall: When the spins at the boundaries **changes abruptly**, then the anisotropic energy becomes very less. Since the anisotropic energy is directly proportional to the thickness of the wall, this leads to a thin Bloch wall.



4. Magnetostriction energy

When a material is magnetized, it is found that it suffers a change in dimensions. This phenomenon is known as **Magnetostriction**. This deformation is different along different crystal directions. So if the domains are magnetized in different directions, they will either expand or shrink. This means that work must be done against the elastic restoring forces. The work done by the magnetic field against these elastic restoring forces is called magneto-elastic energy or Magnetostrictive energy.

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MAGNETIC AND DIELECTRIC PROPERTIES OF MATERIALS

DIELECTRIC PROPERTIES OF MATERIALS

3.9 Internal field (or) Lorentz field & Clausius Mosotti equation

When a dielectric material is kept in an external field it exerts a dipole moment in it. Therefore two fields are produced,

1. Due to external field
2. Due to dipole moment

These long range fields are called internal field (or) local field.

Lorentz method to finding internal field

Let us assume a dielectric material is kept in an external electric field. Consider an imaginary sphere in the solid dielectric of radius ' r '.

Here the radius of the sphere is greater than the radius of the atom, because there are many dipoles within the sphere. An elemental ring is cut with thickness ' ds ' and ' y ' is the radius of the ring.

The electric field at the center of the sphere is called internal field, which is arises due to the following four factors,

$$E_{int} = E_1 + E_2 + E_3 + E_4 \dots\dots\dots (1)$$

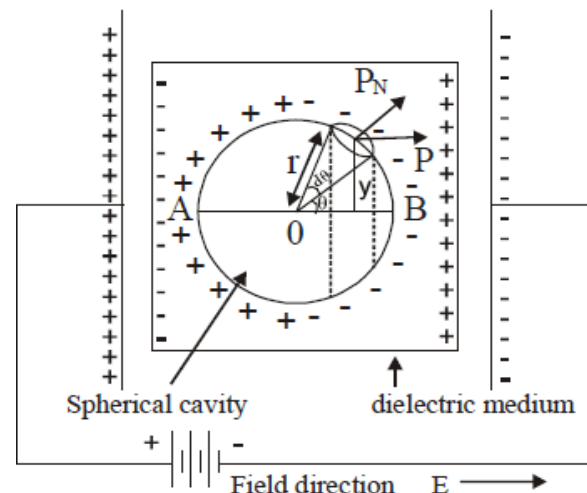
Where,

E_1 - Electrical field intensity due to the charges on the electrodes

E_2 - Electric field due to polarization charges on the plane surface of the dielectric.

E_3 - Electric field due to polarized charges induced at the spherical surface.

E_4 - Electric field due to atomic dipoles inside the sphere.



Macroscopically we can take intensity E_1 and E_2 is equal to the external field

$$E = E_1 + E_2$$

If we consider the dielectric is highly symmetric, the short range forces due to dipole moments inside the cavity becomes zero

i.e. $E_4 = 0$

Now the equation (1) can be rewritten as

$$E_{int} = E + E_3 \quad \dots\dots\dots (2)$$

Calculation of E_3

In the elemental ring, let be the charge on the area ' dA '. Polarization is defined as the surface charges per unit area. Polarization component is perpendicular to the area.

$$p_N = P \cos\theta = q'/dA$$

$$q' = P \cos\theta dA \quad \dots\dots (3)$$

The electric field at the center of cavity due to charge is

$$dE_3 = \frac{q'}{4\pi\epsilon_0 r^2} \dots\dots\dots (4)$$

Substituting equation (3) in equation (4) we get

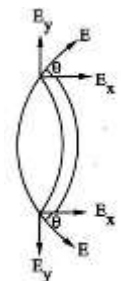
$$dE_3 = \frac{P \cos\theta dA}{4\pi\epsilon_0 r^2} \dots\dots\dots (5)$$

The above intensity is along the radius ' r '. Resolving the intensity into two components. Component parallel to the field direction is

$$E_x = dE_3 \cos\theta$$

$$E_x = \frac{P \cos^2\theta dA}{4\pi\epsilon_0 r^2} \dots\dots\dots (6)$$

Component perpendicular to the field direction is



$$E_y = dE_3 \sin\theta$$

$$E_y = \frac{P \cos\theta \sin\theta dA}{4\pi\epsilon_0 r^2} \dots\dots\dots(7)$$

The perpendicular components are in opposite directions and hence cancel each other. So the parallel components are alone taken into consideration

$$dE_3 = E_x \frac{P \cos^2\theta \sin\theta dA}{4\pi\epsilon_0 r^2} \dots\dots\dots(8)$$

Consider a ring of area dA

$$\begin{aligned} dA &= \text{circumference} \times \text{thickness} \\ &= 2\pi r \sin\theta \cdot r d\theta \\ dA &= 2\pi r^2 \sin\theta d\theta \dots\dots\dots(9) \end{aligned}$$

substituting equation(9) in (8),
we get

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

$$dE_3 = \frac{P \cos^2\theta \sin\theta d\theta}{2\epsilon_0} \dots\dots\dots(10)$$

Electrical field intensity due to the whole sphere can be derived by integrating equation (10) within the limits 0 to π .

$$\int dE_3 = E_3 = \int_0^\pi \frac{P \cos^2\theta \sin\theta d\theta}{2\epsilon_0} \dots\dots\dots(11)$$

$$\int_0^\pi \cos^2\theta \sin\theta d\theta = 2/3$$

Substituting the above value in equation (11) we get

$$E_3 = \frac{2}{3} \cdot \frac{P}{2\epsilon_0}$$

$$E_3 = \frac{P}{3\epsilon_0} \dots \dots \dots (12)$$

Substitute equation (12) in (2) we get,

$$E_{int} = E + E_3$$

$$E_{int} = E + \frac{P}{3\epsilon_0} \dots \dots \dots (13)$$

Where E_{int} is known as the internal field or Lorentz field.

Clausius-Mosotti Equation

Then total polarization,

$$P = NaE_{int}$$

$$E_{int} = \frac{P}{Na}$$

We know that

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

By rearranging we get,

$$\begin{aligned} (\epsilon - \epsilon_0)E &= P \\ E &= \frac{P}{(\epsilon - \epsilon_0)} \dots \dots \dots (2) \end{aligned}$$

Internal field is given by

$$E_{int} = E + \frac{P}{3\epsilon_0} \dots \dots \dots (3)$$

Sub equation (2) in (3), we get

$$E_{int} = \frac{P}{(\epsilon - \epsilon_0)} + \frac{P}{3\epsilon_0}$$
$$= \frac{P[3\epsilon_0 + (\epsilon - \epsilon_0)]}{3\epsilon_0(\epsilon - \epsilon_0)}$$

$$E_{int} = \frac{P(2\epsilon_0 + \epsilon)}{3\epsilon_0(\epsilon - \epsilon_0)} \dots \dots \dots (4)$$

Comparing equation (1) and (4) we get,

$$\frac{P}{Na} = \frac{P(2\epsilon_0 + \epsilon)}{3\epsilon_0(\epsilon - \epsilon_0)}$$

$$\frac{Na}{3\epsilon_0} = \frac{(\epsilon - \epsilon_0)}{2\epsilon_0 + \epsilon}$$

$$\frac{Na}{3\epsilon_0} = \frac{\epsilon_0(\epsilon/\epsilon_0 - 1)}{\epsilon_0(\epsilon/\epsilon_0 + 2)}$$

$$\frac{Na}{3\epsilon_0} = \frac{\epsilon_r - 1}{\epsilon_r + 2} \dots \dots \dots (5)$$

Where ϵ_r dielectric constant. The above equation is known as Clausius-Mosotti Equation.

This equation gives us relation between dielectric constant (ϵ_r) and polarizability

UNIT-III

MAGNETIC AND ELECTRICAL PROPERTIES OF MATERIALS

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3.1. Basic definitions

3.2. Origin of magnetic moment

Introduction

Magnetic materials widely used in nuclear magnetic resonance equipment's and particle accelerators etc. These devices play vital role in our modern living. The knowledge about the origin and the behavior of magnetic materials will be of great help in proper utilization of such devices.

3.1. Basic definitions

Magnetic field

Space around the magnet is called magnetic field.

Magnetic dipole

Magnetic dipole is a system consisting of two equal and opposite magnetic pole separated by a small distance (l).

Magnetic dipole moment

The dipole moment of a magnet is defined as the product of its pole strength (m) and the distance between two poles (l). Unit -Weber/m.

$$\text{Magnetic moment} = m \times l$$

Magnetic flux (Φ)

The number of magnetic lines of force passing through a surface is known as magnetic flux. It is represented by the symbol Φ . Unit -Weber

Magnetic flux density (or) magnetic Induction (B)

Magnetic flux density is defined as the number of magnetic lines of force passing through a unit area of cross-section.

$$B = \Phi/A \quad (\text{Weber/m}^2)$$

Intensity of magnetization (I)

It is the measure of magnetization of a magnetized specimen. It can also be defined as the magnetic moment per unit volume.

$$I = M/V \quad (A/m)$$

Magnetic field intensity (H)

It is defined as the force experienced by a unit north pole placed in a magnetic field.

$$H = F/m \quad (A/m)$$

Magnetic permeability (μ)

It is defined as the ratio of the magnetic flux density to the applied magnetic field intensity

$$\mu = B/H \quad (\text{Henry/m})$$

Relative permeability (μ_r)

It is the ratio between the absolute permeability of a medium to the permeability of a free space.

$$\mu_r = \mu / \mu_0 \quad (\text{No unit})$$

Magnetic susceptibility (χ)

It is the ratio of intensity of magnetization induced in it to the magnetizing field

$$\chi = I/H$$

Relation between χ and μ

We know that the magnetic induction is,

$$B = \mu H$$

This equation can be written in another way as

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

$$= \mu_0 H ((I/H) + 1)$$

$$B = \mu_0 H (\chi + 1)$$

$$B/H = \mu_0 (\chi + 1)$$

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

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

$$\mu_r = 1 + \chi$$

3.2. Origin of magnetic moment

The magnetic moment of a material originates from the orbital and spin motion of electrons in an atom. The permanent magnetic moment arises due to the

- ❖ Orbital angular momentum of the electron
- ❖ Spin angular momentum of the electron
- ❖ Nuclear magnetic moment

Orbital angular momentum of the electron

The orbital motion of electron revolving about a nucleus is equivalent to a tiny current loop.

This produces a magnetic moment perpendicular to the plane of the orbit.

Let us consider an electron moving with constant speed “ v ” in a circular radius “ r ”. Let “ T ” be time taken for one revolution and “ e ” be the charge of the electron.

Magnetic moment associated with the orbit is,

$$\mu_L = \text{current} \times \text{Area of the orbital (loop)} \dots \dots (1)$$

The current I across at any point in the orbit is,

$$I = \frac{\text{Charge of the electron}}{\text{Time}}$$

$$I = \frac{-e}{T} \dots \dots \dots (2)$$

$$\text{Area of the orbital (loop) is} = \pi r^2 \dots \dots \dots (3)$$

Substitute equation (2) and (3) in equation (1), we get

$$\mu_L = -\frac{e\pi r^2}{T} \dots \dots \dots (4)$$

Since, T is time taken by electron for one complete revolution. The distance (Circumference of the orbit) travelled by an electron in a given time (T) is called velocity.

$$\text{Velocity } (v) = \frac{2\pi r}{T} \text{ or } T = \frac{2\pi r}{v}$$

Substitute T in equation (4), we get,

$$\mu_L = -\frac{e\pi r^2}{2\pi r/v}$$

$$\mu_L = -\frac{evr}{2} \dots \dots \dots (5)$$

Dividing and multiplying the RHS of equation (5) by m (mass of the electron), we get

$$\mu_L = -\frac{mevr}{2m}$$

$$\mu_L = -\frac{eL}{2m} \dots \dots \dots (6)$$

Where, $L = mvr$ is the orbital angular momentum of the electron. The equation (6) is the final expression for the magnetic moment associated with the orbital motion of the electron.

Bohr Magnetron

The magnetic moment associated with the orbital magnetic moment of the electron is

$$\mu_L = -\frac{eL}{2m} \dots \dots \dots (1)$$

According to the quantum theory, orbital angular momentum is,

$$L = n\hbar$$
$$L = \frac{nh}{2\pi} \dots \dots \dots (2)$$

Where, n is the orbital angular momentum quantum number and substitute equation (2) in equation (1) we the Bohr magnetron,

$$\mu_B = -\frac{enh}{2\pi m} \dots \dots \dots (3)$$

This is the final expression for Bohr magnetron and the value is calculated by the substitution of all the constants in equation (3). The calculated Bohr magnetron value is $\mu_B = 9.724 \times 10^{-24}$

Spin angular momentum of the electron

Similar to orbital motion, magnetic moment due to spin motion of the electron is given by,

$$\mu_s = -\frac{eS}{m}$$

Where, S is the spin angular momentum and it is given by,

$$S = \frac{sh}{2\pi}$$

Where, s is the spin quantum number and it takes $+1/2$ or $-1/2$.

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MAGNETIC AND ELECTRICAL PROPERTIES OF MATERIALS

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3.3. Microscopic Classification Magnetic Materials

3.3.1. Comparison of Dia, Para and Ferromagnetism

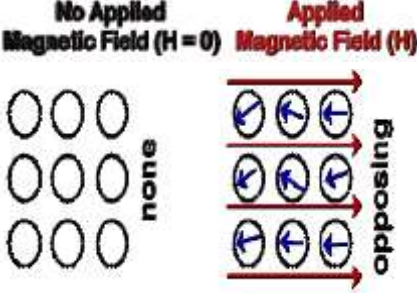
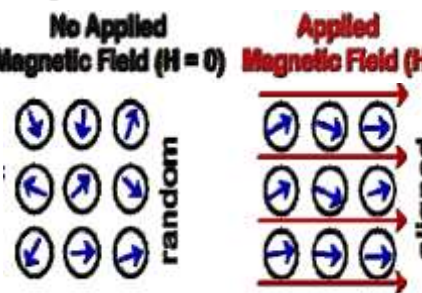
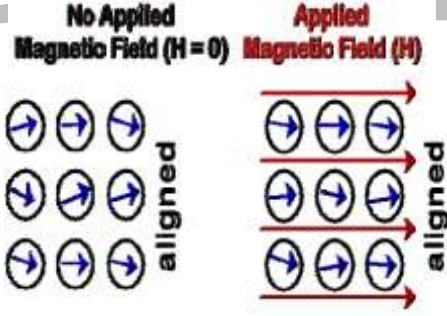
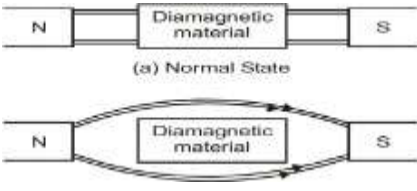
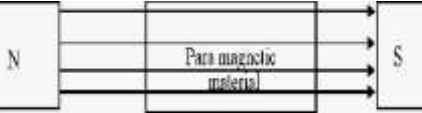

3.3.2. Antiferromagnetism

3.3.3. Ferrimagnetism and Ferrites

3.4 Types of magnetic materials

3.3. Microscopic Classification Magnetic Materials

3.3.1. Comparison of Dia, Para and Ferromagnetism

S. No	Dia Magnetism	Para Magnetism	Ferro Magnetism
1.	There is no permanent magnetic moment in this material	It has permanent magnetic moment	It has enormous permanent magnetic moment
2.	No spin alignment 	Random alignment 	Parallel and Orderly alignment 
3.	Repulsion of magnetic lines of force from center of the material. 	Attraction of magnetic lines of force towards the center. 	Heavy attraction of magnetic lines of force towards center. 

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4.	Permeability is less than 1	Permeability is greater than 1	Permeability is very much greater than 1
5.	Susceptibility is negative	Susceptibility is positive and low	Susceptibility is positive and high
6.	It is independent of Temperature	It is dependent of Temperature $\chi = \frac{C}{T}$	It is dependent of Temperature $\chi = \frac{C}{T - \theta}$
7.	Below critical temperature, it behaves as superconductors.	Below Curie temperature, it is converted into dia magnetic.	Above Curie temperature, It is converted into paramagnetic.
8.	Examples: Au, Ge, Si, Sb, Bi, etc.	Examples: MnSO ₄ , CuSO ₄ , Al, etc.	Examples: Ni, Co, Fe, Steel etc.

3.3.2. Antiferromagnetism

The spins are aligned in antiparallel manner due to unfavorable exchange interaction among them resulting in zero magnetic moment. Even when the field is increased, it has almost zero induced magnetic moment.

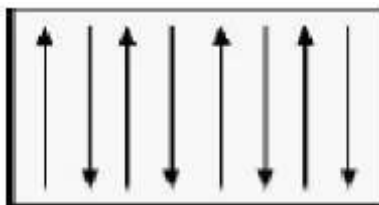


FIG 3.3.1 : Allignment Of Magnetic Moment

Properties

1. The susceptibility is very small and is positive. It is given by

$$\chi = \frac{C}{T + \theta} \quad \text{for } T > T_N \text{ Where } T_N \text{ is the Neel temperature.}$$

2. Initially, the susceptibility increases slightly as the temperature increases and beyond a particular temperature is known as Neel temperature, the susceptibility decreases with temperature.

E.g.: Ferrous oxide, manganese oxide, chromium oxide.

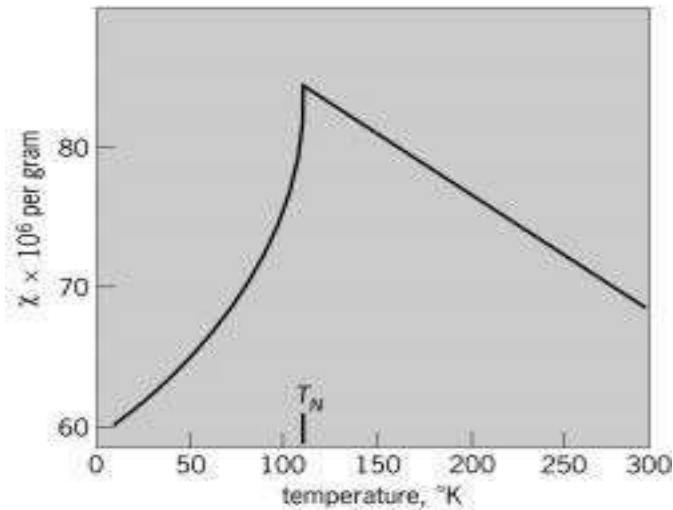
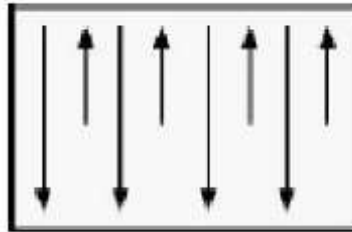


Fig 3.3.2. Variation of susceptibility with temperature

3.3.3. Ferrimagnetism and Ferrites

It is a special class of magnetic material and it is composed of two sets of different transition metal ions having different values of magnetic moment with antiparallel alignment.



Hence these materials have antiparallel magnetic moments of different magnitudes, giving rise to a fairly large magnetic moment in the presence of external magnetic field.

Properties

1. The susceptibility is very large and is positive represented by,

$$\chi = \frac{C}{T \pm \theta} \text{ When } T > T_N.$$

2. Beyond the Neel temperature, χ decreases.
3. These materials have low eddy current losses and low hysteresis losses.
4. They have hysteresis loop in the form of a square and will have low coercivity.

Structure of Ferrites

Ferrites are the magnetic compounds consisting of two or more different kind of atoms. Generally ferrites are expressed as $X^{2+}\text{Fe}_2^{3+}\text{O}_4$. Where, X^{2+} stands for suitable divalent metal ion such as, Mg^{2+} , Zn^{2+} , Fe^{2+} , Mn^{2+} etc.

Example

1. If X^{2+} is replaced by Ni^{2+} , then the ferrite ($Ni^{2+}Fe_2^{3+}O_4$) is formed, thus named as nickel ferrite.
2. If X^{2+} is replaced by Fe^{2+} , then the ferrite ($Fe^{2+}Fe_2^{3+}O_4$) is formed, thus named as ferrous ferrite.

Ferrites formed usually have a face centered cubic structure of ions closely packed together with the divalent and trivalent metal ions in the interstitial sites. This structure is called *spinal structure*.

There are two types of ferrite structure.

- ❖ Regular spinal structure
- ❖ Inverse spinal structure

Regular spinal structure

In this type each metal ion is surrounded by four O^{2-} ions in a tetragonal fashion. For example, if the metal ion is Mg^{2+} , then the structure is shown in below figure and it is called 'A' site. Totally in a unit cell, there will be 8 tetrahedral sites.

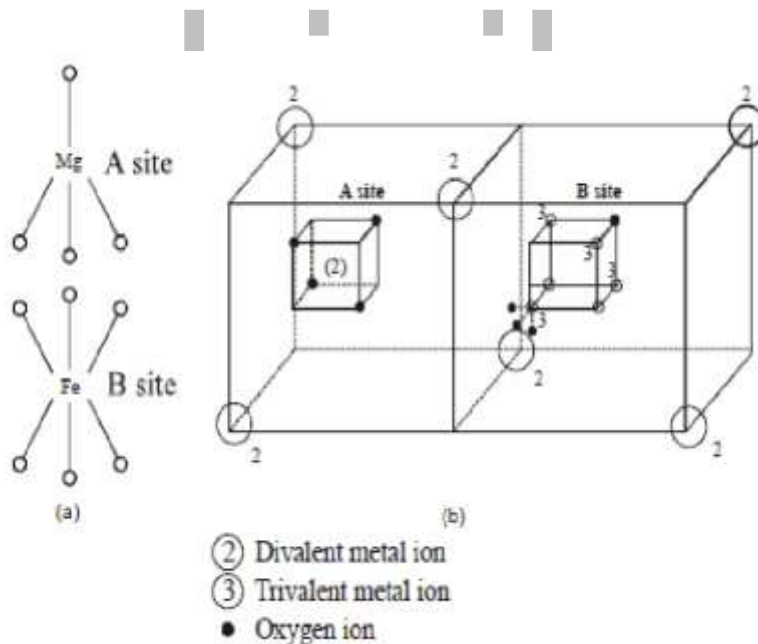


Fig 3.3.3.Regular spinal structure

Each Fe^{3+} is surrounded by six O^{2-} ions and forms an octahedral fashion, which is shown in above figure. Totally there will be 16 such octahedral sites in the unit cell. This is indicated by 'B' site.

Thus in a regular spinal, each divalent metal ion exist in a tetrahedral form and each trivalent metal ion exist in an octahedral fashion. Hence the sites are A and B continue together to form a regular spinal ferrite

Inverse spinal structure

In this, the Fe^{3+} ions occupies all the A sites and half of the B sites also. Thus the left out B sites will be occupied by the divalent (Fe^{2+}). The inverse spinal structure is shown in given figure.

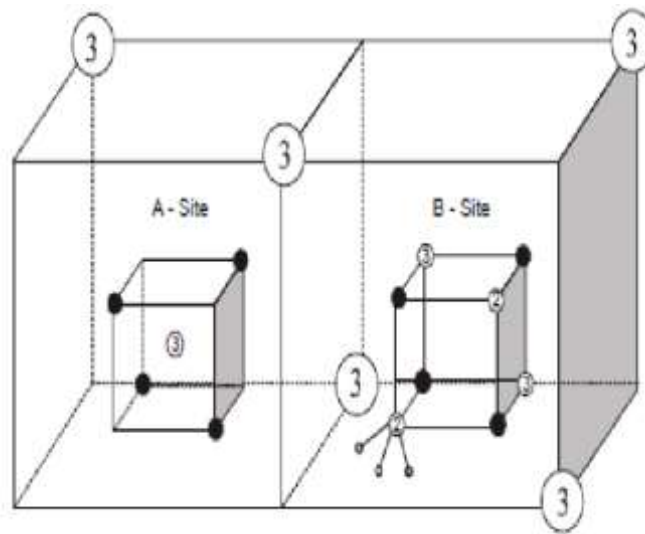


Fig 3.3.4. Inverse spinal structure

Type of interaction present in the ferrites

The spin arrangement between the A site and B site is an antiparallel manner and it was explained by Neel. According to him, in ferrites, the spin arrangement is antiparallel and there exist some interaction between the A site and B sites which is represented as AB interaction

The tendency of AB interaction is to align all spins parallel to each other and antiparallel to all B spins, but the tendency of AA and BB interaction is to spoil the parallel arrangement of A and B spins respectively.

Since AB is very strong as compared with AA and BB, the effect of AB interaction dominates and gives rise to antiparallel spin alignment.

Applications of Ferrites

- ❖ It is used to produce ultrasonic waves by magnetostriction principle
- ❖ It is used in audio and video transformers
- ❖ It is used in radio receivers
- ❖ It is used to amplifier input signals with low noise
- ❖ It is used to as a power limiters
- ❖ It is used in computer and data processing circuit
- ❖ It is used as Gytrators, circulator and Isolator

3.4 Types of magnetic materials

Soft and Hard Magnetic Materials

S.No	Soft magnetic materials	Hard magnetic materials
1	They can be easily magnetized and demagnetized	They cannot be easily magnetized and demagnetized
2	They have narrow hysteresis loop	They have broad hysteresis loop
3	Hysteresis loss is small due to small hysteresis loop area.	Hysteresis loss is large due to large hysteresis loop area.
4	Coercivity and retentivity are small.	Coercivity and retentivity are large.
5	They have low eddy current loss	They have large eddy current loss
6	Magnetic energy stored is small.	Magnetic energy stored is large.
7	Susceptibility and permeability are large.	Susceptibility and permeability are small.
8	Movement of domain wall is easy and hence large magnetization is produced even for small applied field.	Movement of domain walls is difficult due to the presence of impurities. Hence large field is required to produce required magnetization.
9	They are free from strains and impurities.	They have impurities and large defects.
10	E.g. Ferrites, Iron, Garnet, Silicon alloys.	E.g., Tungsten steel, cobalt steel, carbon steel.
11	They are used to make temporary magnets. They are also used in switching devices, electromagnets, matrix storage computers.	They are used to make permanent magnets. These magnets are used in magnetic detectors, microphones and magnetic separators.

Unit – III

MAGNETIC AND DIELECTRIC PROPERTIES OF MATERIALS

DIELECTRIC PROPERTIES OF MATERIALS

3.7 Introduction

Dielectrics are the materials for which all the electrons are tightly bounded to their parent molecule. All dielectrics are insulators, but it slightly differs from insulators because dielectrics are used to store electrical energy.

Examples: Glass, Mica, Rubber, Paper, Wood,
Ceramic, Ebonite

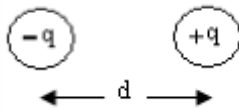
Properties of dielectrics

1. Dielectrics are non-metals with high resistivity
2. They have very large energy gap of more than 3eV
3. The electrical conductivity of dielectric is very low because there are no free electrons to carry charges
4. They have negative temperature coefficient of resistance and high insulation resistance

Basic definitions

Electric Dipole

Two equal and opposite charges ($+q, -q$) separated by a small distance (d) is called electric dipole.



Dipole moment (μ)

The product of the magnitude of the charge (q) and distance between two charges (d) is called as dipole moment

Dipole moment $\mu = q \cdot d$

Its unit is Coulomb- meter

Permittivity (ϵ)

Permittivity represents the dielectric property of the medium. Permittivity of free space is $\epsilon_0 = 8.854 \times 10^{-12}$ Farad/meter

Electric displacement vector (D)

The electric displacement vector (D) is a quantity which is a convenient function for analyzing the electrostatic fields in the dielectrics. It is given by

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

Dielectric Constant(ϵ_r)

It is the ratio between the permittivity of a medium (ϵ) and the permittivity of free space (ϵ_0).

$$\epsilon_r = \epsilon / \epsilon_0$$

Polarization

The process of producing electric dipoles by the application of an external electric field is called polarization in dielectrics.

Polarisability

We know that average dipole moment (μ) is proportional to the applied electrical field (E)

$$\bar{\mu} = \alpha E$$

Where α is the polarisability

$$\alpha = \frac{\bar{\mu}}{E}$$

Polarisability is defined as the ratio of the average dipole moment per unit electrical field applied. Its unit is Farad-metre²

Polarization vector (p)

It is defined as the dipole moment per unit volume

$$\vec{P} = \frac{\mu}{V}$$

Its unit is Coulomb – meter⁻²

Polar molecules

Molecules have permanent dipole moment even in the absence of an applied field is called polar molecules.

Example: CHCl₃, H₂O, HCl

Non polar molecules

Molecules do not have permanent dipole moment is called non-polar molecules. Example: CCl_4 , CO_2 , H_2

Active dielectrics

When a dielectric is subjected to an external electric field, if the dielectric actively accepts the electricity, then they are termed as active dielectrics. Thus active dielectrics are the dielectrics which can easily adopt itself to store the electrical energy in it.

Example: Piezoelectric, ferroelectrics, pyro electric

Passive dielectrics

These dielectrics are also called insulating materials. As the name itself suggests conduction will not take place through these dielectrics. Thus passive dielectrics are the dielectrics which restrict the flow of electrical energy in it.

Example: Glass, Mica, Plastic

3.8 Various polarization mechanisms in dielectrics

The application of an electric field to a dielectric material creates the dipoles resulting in polarization. There are four different types of polarization namely

- (i) Electronic (or) Induced polarization
- (ii) Ionic (or) atomic polarization
- (iii) Orientation polarization
- (iv) Space-charge (or) Interfacial polarization

3.8.1. Electronic (or) Induced polarization

Electronic polarization occurs due to the displacement of positively charged nucleus and negatively charged electrons in opposite directions, when an external electric field is applied.

Induced dipole moment is

$$\mu = \alpha_e E \quad \text{_____}(1)$$

Where, α_e is known as electronic polarizability. Monoatomic gases exhibit this kind of polarization. It is proportional to the volume of the atoms and independent of temperature.

Calculation of electronic polarizability (α_e)

a) Without field

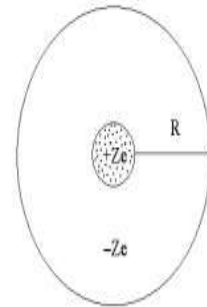
Let us consider a classical model of an atom. Assume the charge of nucleus of that atom is $(+Ze)$. The nucleus surrounded by an electron cloud of charge $(-Ze)$, which is distributed throughout the sphere (atom) of radius R .

The charge density ' ρ ' of the electrons

$$\rho = \frac{\text{Total negative charge}}{\text{Volume of the atom}}$$

The charge density ' ρ ' of the electrons $= \frac{-Ze}{\frac{4}{3}\pi R^3}$

Charge density $= \frac{-3Ze}{4\pi R^3}$ (2)



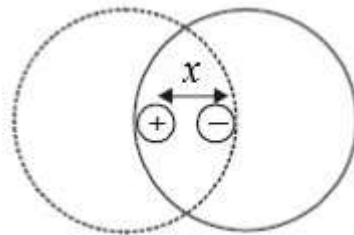
b) With field

If the dielectric material is placed in an electric field of strength E , two phenomena occurs,

Lorentz force: which is tends to separate the nucleus and the electron cloud from their equilibrium position. The positive nucleus will move towards the field direction and the electron cloud will move in the opposite direction of field.

Coulomb force: It arises between the nucleus and the electron cloud which will tend to maintain the original equilibrium position.

Let ' x ' be the displacement made by the electron from the positive core as shown in figure.



Here the displacement of electron cloud is proportional to applied electric field (E)

Induced dipole moment (μ_e) = Magnitude of charge x Displacement

$$= Z e x \dots \dots \dots (3)$$

Since the core is heavy, it will not move when compared to the movement of electron cloud. Here, $x \ll R$. Since Lorentz and coulomb forces are equal and opposite in nature, equilibrium is reached.

At equilibrium,

Lorentz force = Coulomb force

We know that,

Lorentz force (F_L) = Charge x Electric field

$$= - ZeE \dots\dots\dots(4)$$

$$\text{Coulomb force } (F_C) = \frac{QZe}{4\pi\epsilon_0 x^2} \quad (5)$$

Total number of negative charges (Q) enclosed in the sphere of radius x = charge density charges of electrons x Volume of the sphere

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

$$Q = \frac{-Zex^3}{R^3} \dots\dots\dots (6)$$

Substitute eqn. (6) in (5) we get,

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

$$F_c = \frac{-Z^2 e^2 x}{4\pi\epsilon_0 R^3} \dots\dots\dots (7)$$

At equilibrium position,

$$\text{Equation (4)} = \text{equation (7)}$$

Therefore by substitution we get

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

$$E = \frac{-Zex}{4\pi\epsilon_0 R^3}$$

$$x = \frac{4\pi\epsilon_0 R^3 E}{Ze} \dots\dots\dots (8)$$

Substitute the value of 'x' in eqn. (3) we get

$$\mu_e = \frac{Ze4\pi\epsilon_0 R^3 E}{Ze}$$

$$\mu_e = 4\pi\epsilon_0 R^3 E \quad \text{-----} (9)$$

Compare eqn. (9) and (1) we get,

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

$$\alpha_e = 4\pi\epsilon_0 R^3 \quad \text{-----} (10)$$

Where α_e is called electronic polarization

Conclusion:

- ❖ Electronic polarization is independent of temperature.
- ❖ It is proportional to the volume of atoms in the material
- ❖ Electronic polarization takes place in all dielectrics

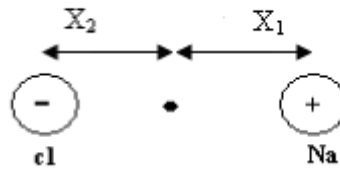
3.8.2 Ionic polarization

Ionic polarization occurs due to the displacement of positive and negative ions in opposite directions, when an external electric field is applied. This type of polarization is produced in ionic molecules such as NaCl, KBr, and KCl etc.

Let us now consider a NaCl crystal. Each Na^+ and Cl^- is a natural dipole as shown in figure.



In the presence of electric field, the ions are separated in an opposite directions as shown in given figure.



The Na^+ ion moved a bit right for a distance say ' x_1 ', and Cl^- moved a bit left for a distance say ' x_2 '.

Induced dipole moment

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

When the field is applied, the restoring force produced is proportional to the displacement of the positive ion

For positive ion

Restoring force $F \propto x_1$
 Or $F = \beta_1 x_1 \text{ (2)}$

For negative ion

Restoring force $F \propto x_2$
 Or $F = \beta_2 x_2 \text{ (3)}$

Here β_1 and β_2 are restoring force constants, which depend on the masses of the ions and the angular frequency of the molecule. If m is the mass of positive ion and M is the mass of negative ion and ω_0 is the angular frequency

$$\beta_1 = m\omega_0^2 \dots\dots\dots (4)$$

$$\beta_2 = M\omega_0^2 \dots\dots\dots (5)$$

Where ω_0 = angular frequency

Substituting for β_1 in equation (2), the restoring force for positive ion can be written as

$$F = m\omega_0^2 x_1 \dots\dots\dots (6)$$

We know that

$$F = eE \dots\dots\dots (7)$$

Equating eqn.(6) and (7) we get

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

Therefore,

$$x_1 = \frac{eE}{m\omega_0^2} \dots\dots\dots (8)$$

Similarly for the negative ion we can write

$$x_2 = \frac{eE}{M\omega_0^2} \dots\dots\dots (9)$$

Adding eqn.(9) and (10) we get

$$x_1 + x_2 = \frac{eE}{\omega_0^2} \left(\frac{1}{m} + \frac{1}{M} \right) \dots\dots\dots (10)$$

Substitute equation(11) in eqn. (1) we get

$$\mu_i = \frac{e^2 E}{\omega_0^2} \left(\frac{1}{m} + \frac{1}{M} \right) \dots\dots\dots (11)$$

But, from definition,

$$\mu_i = \alpha_i E \dots\dots\dots (12)$$

Compare equation (12) and (13) we get,

$$\alpha_i E = \frac{e^2 E}{\omega_0^2} \left(\frac{1}{m} + \frac{1}{M} \right)$$
$$\alpha_i = \frac{e^2}{\omega_0^2} \left(\frac{1}{m} + \frac{1}{M} \right) \dots\dots\dots (13)$$

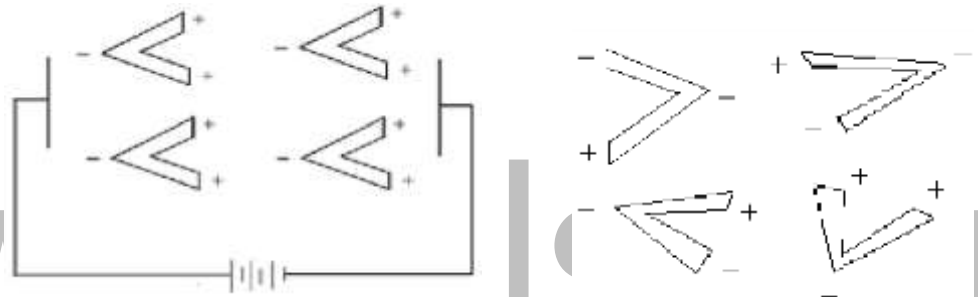
Conclusion

- ❖ So the ionic polarizability is inversely proportional to the square of the natural frequency of the ionic molecule
- ❖ It is directly proportional to reduced mass
- ❖ It is independent of temperature

3.8.3 Orientation polarization

This polarization takes place only in the polar dielectrics. Polar dielectrics have molecules with permanent dipole moments even in the absence of electric field as shown in figure.

When field is applied, positive align with the direction of field and the negative side align with the direction as shown figure.



At H=0

At magnetic field

From the Langevin's theory of Para magnetism, net intensity of magnetization is given by

$$M = \frac{N\mu^2 B}{3K_B T}$$

Since same principle can be applied to the application of electric field in dielectrics.

Orientation polarization

$$P_0 = \frac{N\mu^2 E}{3K_B T} \text{ ----- (1)}$$

$$P_0 = N\alpha_0 E \text{ ----- (2)}$$

Where, N represents the no of atoms and compare equations (1) and (2) we get,

$$N\alpha_0 E = \frac{\mu^2 E}{3K_B T}$$

$$\alpha_0 = \frac{\mu^2}{3K_B T} \text{ ----- (3)}$$

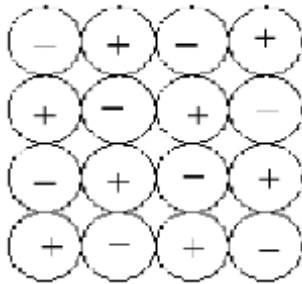
Conclusion

- ❖ The orientation polarizability is inversely proportional to absolute temperature of the material

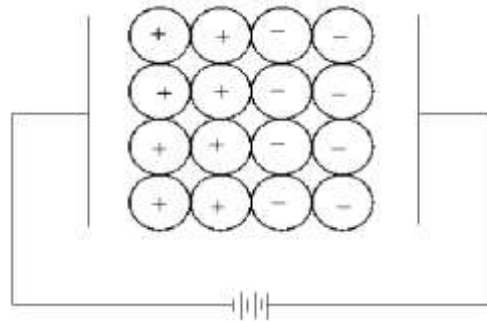
3.8.4 Space charge polarization (or)

The space charge polarization occurs due to diffusion of ions, along the field direction and giving rise to redistribution of charges in the dielectrics.

Consider a dielectric medium placed between any two electrodes. When no field is applied to the electrode the positive and negative charges are not separated as shown in figure.



When an electric field is applied, the positive charges are accumulated near the negative electrode as shown in figure.



Therefore a dipole moment is induced due to the displacement of the ions. Then the induced dipole moment per unit volume gives the induced polarization. This polarization is known as Space charge polarization

Total Electric polarization

The Total Electric polarization is the sum of electronic polarization, ionic polarization, orientation polarization, and space charge polarization. Among these, the space charge polarization is very small compared to others. So it can be neglected

Therefore the total polarizability is given by

$$\alpha = \alpha_e + \alpha_i + \alpha_0$$

$$\alpha = 4\pi \epsilon_0 R^3 + \frac{e^2}{\omega_0^2} \left(\frac{1}{m} + \frac{1}{M} \right) + \frac{\mu^2}{3k_B T} \text{----- (1)}$$

We know that the total polarization is

$$P = NE\alpha \text{----- (2)}$$

Substitute equation (1) in (2) we get,

$$P = NE \left[4\pi \epsilon_0 R^3 + \frac{e^2}{\omega_0^2} \left(\frac{1}{m} + \frac{1}{M} \right) + \frac{\mu^2}{3k_B T} \right]$$

This equation is called Langevin- Debye equation

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