

4. 7.3 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

1. Intrinsic (or) avalanche breakdown

When a dielectric is subjected to electric field then the electrons in the valance 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 depends on the electrodes and shape of the material.
5. It occurs within a short span of time (milliseconds)

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. 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 occur 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 current

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

5. Defect breakdown

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

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

Applications of dielectric materials

1. It is used as a dielectric medium in capacitors.
2. It is used as insulating materials in transformers.
3. It is used in industries and dielectric heating.
4. Dielectrics possessing piezoelectric effect is used in gas lighters, microphones, phonographs.
5. Dielectric heating is the principle used in microwave oven.
6. Dielectric heating is also used in the dehydration of food, tobacco etc.

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4.7 DIELECTRIC MATERIALS

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

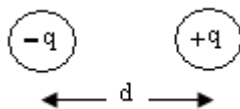
Properties of dielectrics

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

$$\mathbf{D} = \epsilon \mathbf{E} = \epsilon_0 \mathbf{E} + \mathbf{P}$$

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 ($\bar{\mu}$) is proportional to the applied electrical field

$$\bar{\mu} \propto E \quad (E)$$

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

Where α is the polarizability

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

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: CCl₄, CO₂, H₂

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

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4.3. 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.

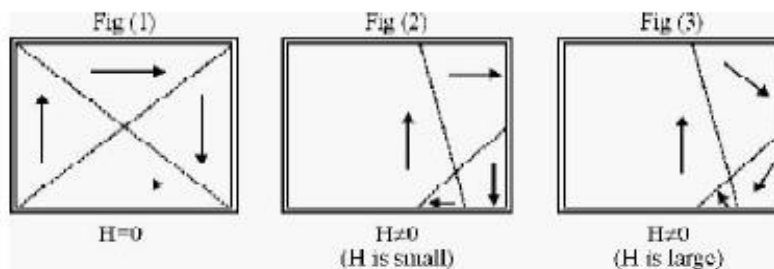
❖ By the rotation of domains.

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.



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

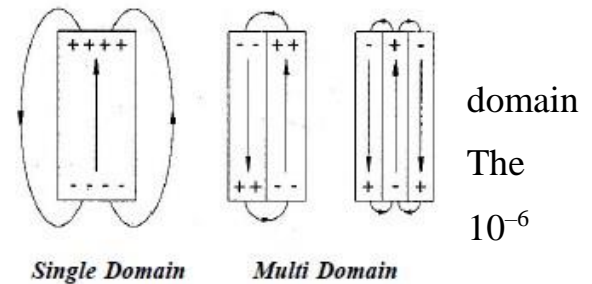
The total internal energy of the domain structure in a ferromagnetic material is made up from the following

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 atomic magnets into a single and this work done is stored as potential energy. volume of the domain may vary between 10^{-2} to 10^{-6} cm^3 .

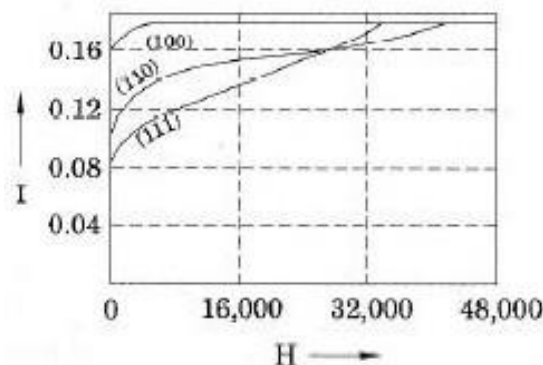


2. Anisotropy energy

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.



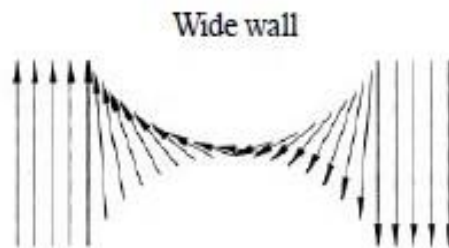
Crystalline anisotropy energy is energy of magnetization which is the function of crystal orientation. As shown in figure magnetization curves for iron with the applied field along different crystallographic directions have been drawn. For example, in BCC iron the easy direction is [100], the medium 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

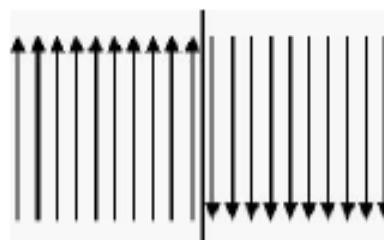
A thin boundary or region that separates adjacent domains in different directions is called domain wall or Bloch wall. The size of the Bloch walls is about 200 to 300 lattice constant thickness. The energy of domain wall is due to both exchange energy and anisotropic energy. Based on the spin alignments,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

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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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4.6 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.

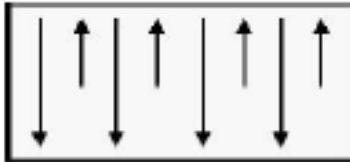


Fig:4.6.1 Magnetic moment alignment

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

Properties

- (i) The susceptibility is very large and is positive represented by,

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

- (ii) Beyond the Neel temperature, χ decreases.
- (iii) These materials have low eddy current losses and low hysteresis losses.
- (iv) They have hysteresis loop in the form of a square and will have low coercivity.

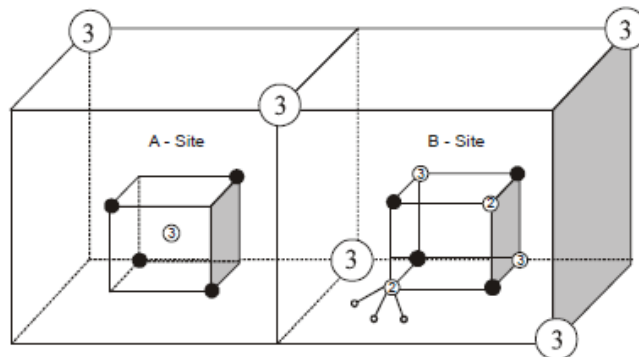
Structure of Ferrites

Ferrites are the magnetic compounds consisting of two or more different kind of atoms.

Generally ferrites are expressed as $X^{2+}Fe_2^{3+}O_4$. 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.

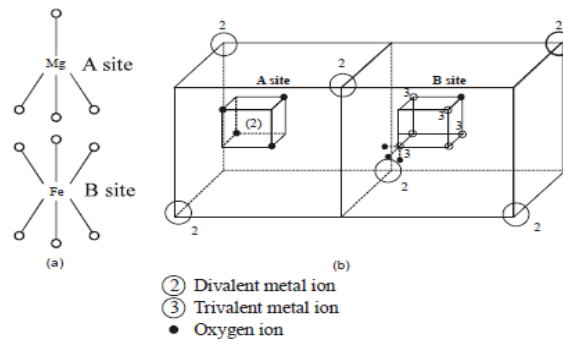


Fig:4.6.2

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 spinel, 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 spinel ferrite

Inverse spinel 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 spinel structure is shown in given figure.

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 amplify input signals with low noise

- ❖ It is used as a power limiter
- ❖ It is used in computer and data processing circuit
- ❖ It is used as gyrators, circulators and isolators

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4.7.4 Ferro electricity and its applications

When a dielectric material exhibits electric polarization even in the absence of external field, it is known as ferroelectricity and these materials are termed as ferroelectrics. Ferroelectrics are anisotropic crystals which exhibit spontaneous polarization.

Examples:

- ❖ Rochelle salt
- ❖ Potassium phosphate
- ❖ Barium titanate
- ❖ Potassium niobate
- ❖ Lithium niobate
- ❖ Lithium tantalate etc.

Properties:

1. The dielectric constant of these ferroelectric materials is above 2000.
2. It will not vary with respect to temperature.
3. The dielectric constant reaches maximum value only at a particular temperature called Curie temperature.
4. The polarization does not varies linearly with respect to electric field.
5. Ferro electrics exhibits electric polarization very easily, even in the absence of external electric field
6. They exhibit domain structure similar to that of ferromagnetic material.
7. Ferro electric materials also exhibit hysteresis.
8. Ferro electric materials exhibit piezo electricity and pyro electricity.
 - Piezo electricity means the creation of electric polarization by mechanical stress.

Pyro electricity means the creation of electric polarization by thermal stress.

Hysteresis of Ferroelectric Materials

The ferroelectrics are known as non-linear dielectrics. Such materials exhibit hysteresis curve similar to that of ferromagnetic materials. The lagging of polarization 'P' behind the applied electric field E is called dielectric hysteresis.

When a ferroelectric material is subjected to external electric field (E) the polarization (P) increases with respect to the field applied and it reaches the maximum value 'OA'. If now the applied electric field is reduced, the polarization also decreases from a, and when E becomes zero a small amount of polarization exists in the material is called spontaneous (or) residual polarization.

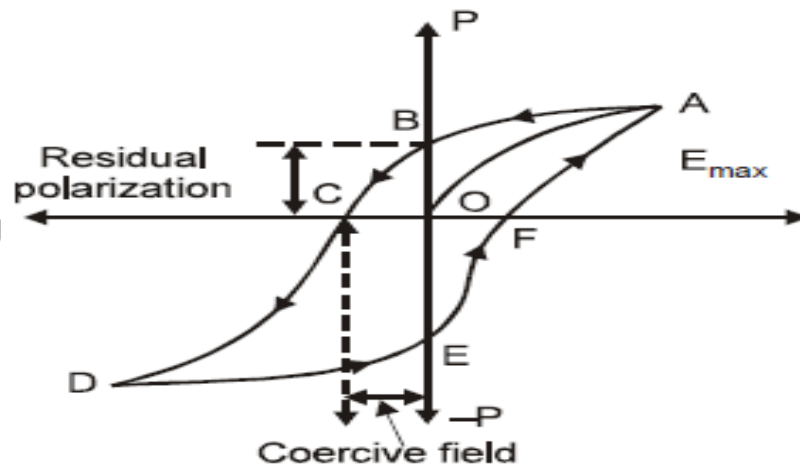
In order to reduce the value of polarization to zero, a reversing electric field 'OC' should be applied. This field is known as coercive field. Thus the variation of 'P' with respect to 'E' traced along the closed path 'ABCDEF A' in one full cycle of polarization and depolarization is called hysteresis or the hysteresis curve.

Applications

1. Ferro electric materials are used to produce ultrasonic
2. Ferro electrics are also used in SONAR, Strain gauges etc.
3. Ferroelectrics are used to measure and control the temperature.
4. They are also used as frequency stabilizers and crystal controlled oscillators.
5. Electrects are the type of ferroelectric material used in the production of capacitor, microphones, gas filters etc

Electrostatic bandages are used over the fractured bones to speed up the healing process.

6. In optical communication the ferroelectric crystals are used for optical modulation
7. Piezo electric materials are used to make pressure transducers, ultrasonic transducers and microphones
8. Pyroelectric materials are used to make high sensitive infra-red detectors.



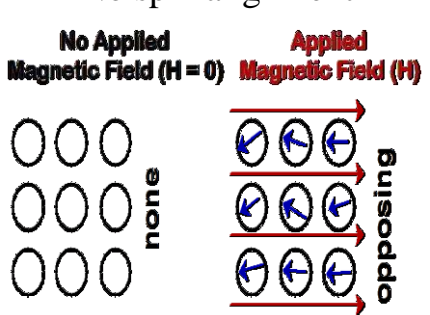
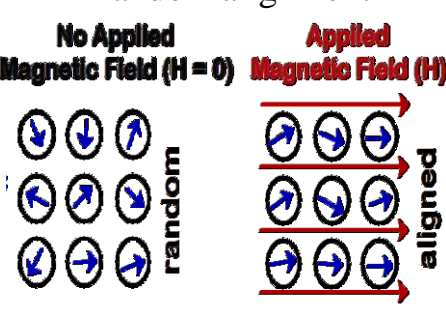
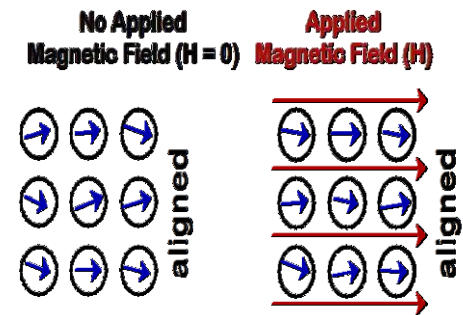
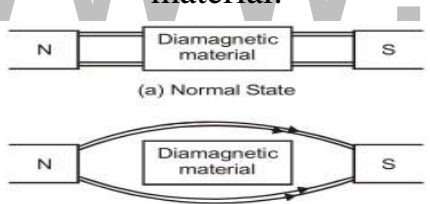
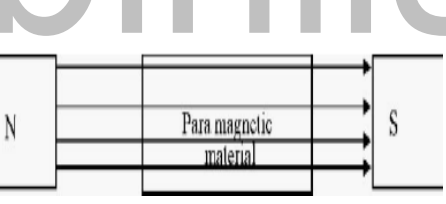
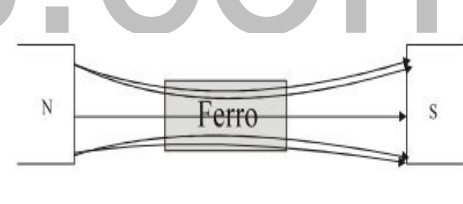
Comparison of Type of Polarization

S. N	Factor	P_e	P_i	P_o	P_s
1	Definition	Electron clouds are shifted from nucleus	Cations and anions are shifted	Regular alignment of random molecules takes place.	Ion diffusion takes place.
2	Examples	Inert gases	Ionic crystals	Alcohol, methane, CH ₃ Cl	Semi conductors, Ferrites.
3	Temperature dependence	Independent	Independent	Dependent	Dependent
4	Relaxation time	Very fast	Slow	Slower	Slowest
5	Power loss	Low	High	Higher	Highest
6	Frequency range	10 ¹⁵ Hz	10 ¹³ Hz	10 ⁶ Hz	10 ⁵ Hz
7	Polarisability	$\alpha_e = \frac{\epsilon_0 (\epsilon_r - 1)}{N}$	$\alpha_i = \frac{e^2}{\omega_0^2} \left[\frac{1}{m} + \frac{1}{M} \right]$	$\alpha_o = \frac{\mu^2}{3KT}$	α_s is negligible

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4.2. Ferro magnetism

4.2.1. 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.	<p>No spin alignment</p> <p>No Applied Magnetic Field ($H = 0$) Applied Magnetic Field (H)</p> 	<p>Random alignment</p> <p>No Applied Magnetic Field ($H = 0$) Applied Magnetic Field (H)</p> 	<p>No Applied Magnetic Field ($H = 0$) Applied Magnetic Field (H)</p>  <p>Parallel and Orderly alignment</p>
3.	<p>Repulsion of magnetic lines of force from center of the material.</p> 	<p>Attraction of magnetic lines of force towards the center.</p> 	<p>Heavy attraction of magnetic lines of force towards center.</p> 
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.

4.2.2 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.



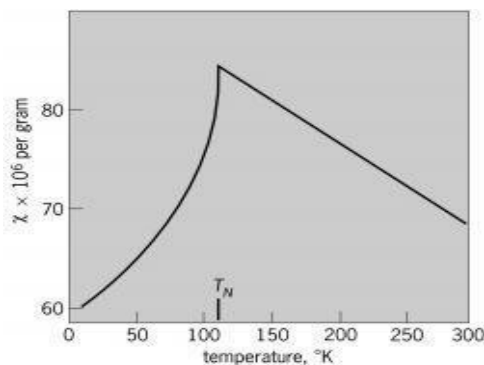
Properties

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.



4.7.2 Frequency and temperature dependence of polarization

On the application of an alternating electric field, the polarization process occurs as a function of time. The polarization $P(t)$ as a function of time ' t ' is given by

$$P(t) = P \left[1 - e^{\left(\frac{-t}{t_r}\right)} \right]$$

Where, ' P ' is the maximum polarization attained on external applied static field and ' t_r ' is the relaxation time for the particular polarization process. The relaxation time is a measure of the time scale of a polarization process. This varies for different polarization process.

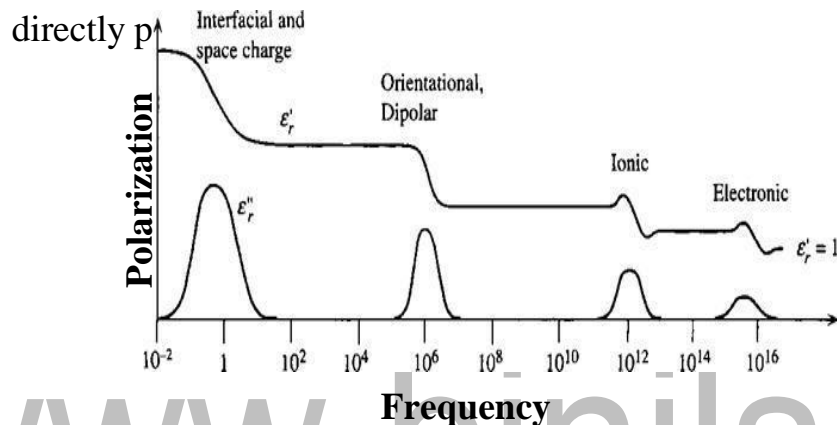
Frequency dependent polarization

1. Electronic polarization is very fast. The frequency of the voltage is very high, which is in the optical range ($\approx 10^{15}$ Hz). Thus it occurs at all frequencies.
2. Ionic polarization is slower than the electronic polarization, because the mass of the ions are heavier than the electrons cloud. It is occurs in the infra-red frequency region (10^{13} Hz).
3. Orientation polarization is slower than the ionic polarization and which is occurs only at electrical frequency (10^6 Hz).
4. Space charge polarization is the slowest process and occurs only at power frequencies (10^2 Hz).
5. Thus at lower frequencies, the value of the total polarization is very high and at higher frequencies (optical frequencies) the value of the total polarization is very small.

Temperature dependence

Generally, orientation and space charge polarizations are depends on temperature, whereas the electronic and the ionic polarization are practically independent of temperature for normal temperatures

1. Orientation polarization decreases with the increase in temperature, because it is inversely proportional to temperature.
2. Space charge polarization increases with the increase in temperature, because it is



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4.4. Hysteresis

When a magnetic material is taken through a cycle of magnetization, the variation of (B) with respect to (H) can be represented by a closed curve. In other words, the lagging of magnetization behind the magnetizing field is known as hysteresis curve.

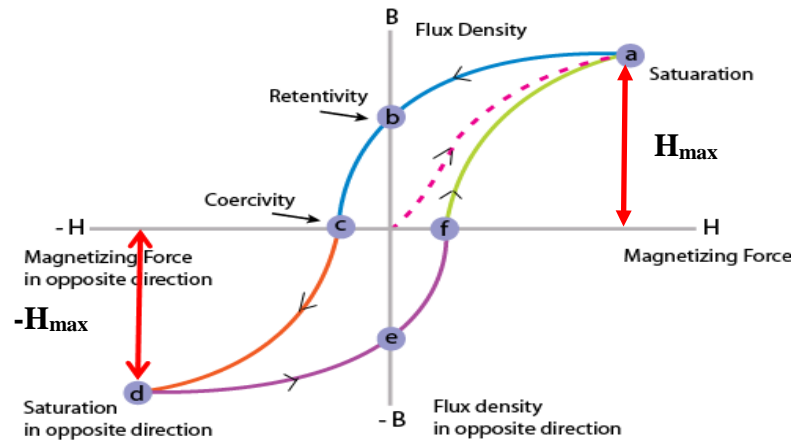


Fig:4.4.1 Hysteresis

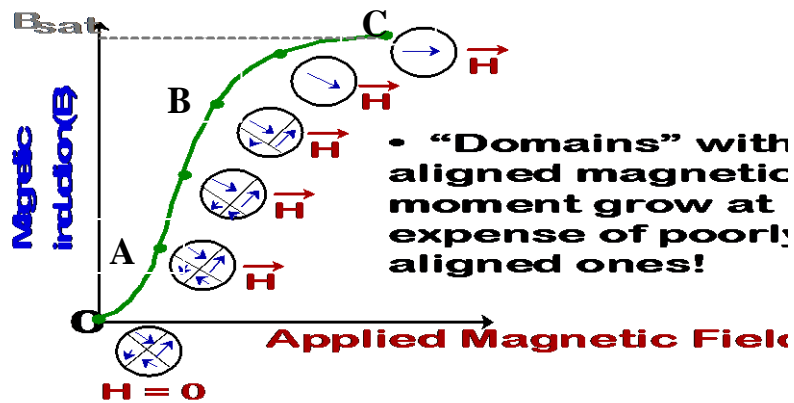
Explanation

If a magnetizing field (H) is applied to a ferromagnetic material and if H is increased H_{max} . The material acquires the magnetism. So the magnetic induction also increases, represented by 'oa' in the above figure.

Now the magnetic field is decreased from H_{max} to zero, the magnetic induction will not fall rapidly to zero. But it falls 'b' rather than zero. This shows that even when the applied field is zero (or) removed, the material still acquires some magnetic induction (ob) which is so called **residual magnetism (or) Retentivity**.

Now, to remove this residual magnetism, the magnetic field strength is reversed and increased to $-H_{max}$ represented as 'oc' so called **coercivity**. Hence, we get the curve 'bcd'. Then the reverse field ($-H$) is reduced to zero and the corresponding curve 'de' is obtained and further increasing H to H_{max} the curve 'efa' is obtained.

4.4.2 Explanation of Hysteresis Curve on The Basis of Domain Theory



When a field is applied, for small H , the domain walls are displaced and gives rise to small value of magnetization. [OA in the graph]. Now, the field is removed, the domains return to its original state known as reversible domains.

When the field is increases, a large number of domains contribute to the magnetization and I increases rapidly with H . Now, when the field is removed the domain boundaries do not come back to the original position due to the domain wall movement to a very large distance (AB in the graph). These domains are called irreversible domains.

Now if the field is further increased, domains start rotating along the field direction and anisotropic energy is stored and it is represented as BC in the graph. Thus the specimen is said to attain maximum magnetization at this position even after the removal of the field is known as Retentivity. This Retentivity can be destroyed by applying a high reverse magnetic field called coercivity.

Thus the reversible and irreversible domain wall movements give rise to hysteresis in the Ferromagnetic materials.

UNIT-IV

MAGNETIC PROPERTIES OF MATERIALS

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.

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.

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

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

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

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

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

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

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

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,

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

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 $-1/2$.

4.5 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.

4.8 Super Conductors and their properties

Super conductors

Super conductors are the materials which has zero resistivity and behaves as dia magnet below its transition temperature.

Transition temperature: The temperature at which the normal conductors changed into superconductor is called transition temperature.

Properties:

1. Electrical resistance: It has zero electrical resistance.
2. Effect of magnetic field :Super conducting property can be destroyed by the application of strong magnetic field.

The minimum field required to destroy the super conducting property is called critical field (H_c).

$$H_c = H_0 (1 - ((T/T_c)^2))$$

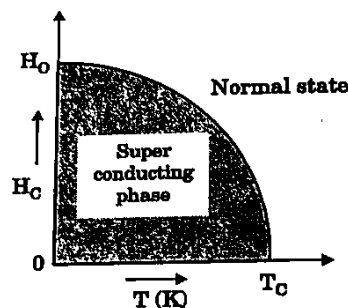


Fig. 6.2 Variation of H_c with T

Effect of heavy current:

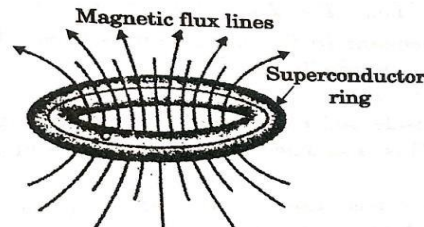
Super conducting property can be destroyed by the application of strong electric field.

Critical current required to destroy the superconducting property is $I_c = 2\pi r c$

3. Persistent current:

When a super conducting ring is placed in a magnetic field , current is produced in the ring.

This current persists in the ring without any



decrease in its value.

This current is called persistent current.

4. Meissner effect:

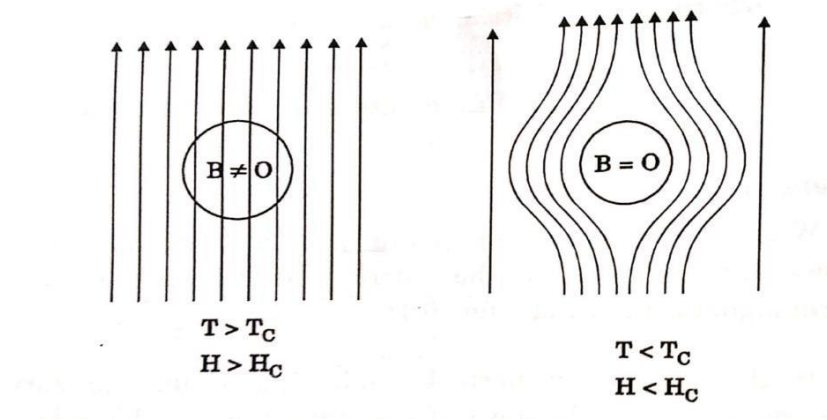
When the material is in normal conducting state the magnetic lines of forces passes through the material.

The material is cooled below its transition temperature the magnetic lines of forces are excluded from the material

Definition:

When a superconducting material is placed in a weak magnetic field and cooled

below its transition temperature the magnetic lines of forces are excluded from the material. This effect is called Meissner effect.



5. Isotope effect: The transition temperature is inversely proportional to the atomic masses.

$$T_c \propto 1/M^\alpha$$

6. Effect of pressure: Transition temperature is proportional to pressure.

7. Effect of stress: Transition temperature is increased by the stress.

4.7.1 Polarization mechanisms in dielectrics

Langevin-Debye Equation

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

4.7.1(i).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

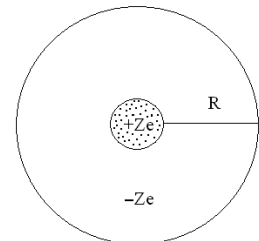
Let us consider a classical model of an atom. Assume the charge of nucleus of that atom is (+Ze). The nucleus surrounded by an electron cloud of charge(-Ze), which is distributed throughout the sphere (atom) of radius R.

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

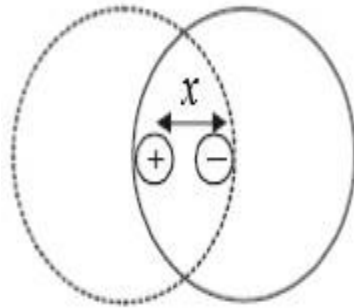
$$\text{Charge density} = \frac{-3Ze}{4\pi R^3} \dots \dots \dots (2)$$



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,

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

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

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

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

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

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

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

At equilibrium position,

Equation (4) = 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

$$\frac{Z}{e} \mu_e Ze 4\pi \epsilon_0 R^3 E$$

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

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

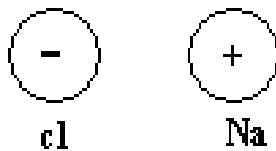
Conclusion:

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

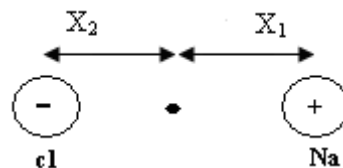
4.7.1(2) Ionic polarization

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 = *Charge* \times *displacement*

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

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

$$\beta_1 = m\omega_0^2 \text{..... (4)}$$

$$\beta_2 = M\omega_0^2 \text{..... (5)}$$

Where ω_0 = angular frequency

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

A

$$F = m\omega_0^2 x_1 \text{.....}$$

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,

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

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

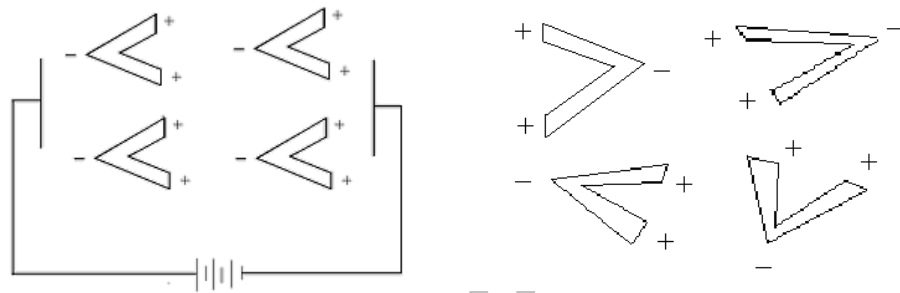
Conclusion

- ❖ 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

4.7.1(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.



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,

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

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

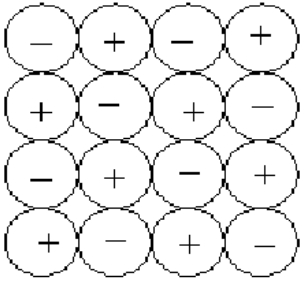
Conclusion

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

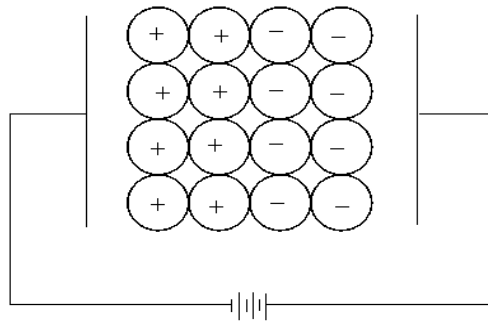
4.7.1(4) Space charge polarization (or)

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