

UNIT III
MAGNETIC AND DIELECTRIC PROPERTIES OF MATERIALS

MAGNETIC MATERIALS

1. TERMS AND DEFINITIONS

Magnetic flux (ϕ)

Total number of magnetic lines of force passing through a surface is known as magnetic flux. It is represented by the symbol ' ϕ ' and its unit

Magnetic flux density (or) Magnetic induction (B)

Magnetic flux density at any point in a m passing normally through unit area of cross section (A) at that point. It is denoted by the symbol B and

its unit is weber / metre² or tesla.

$$B = [\phi / A]$$

Intensity of magnetization (I)

The term magnetization means the process of converting non-magnetic material on magnetic material.

When some amount of external magnetic field is applied to the metals such as iron, steel and alloys etc., they are magnetized to different degrees. The intensity of magnetisation (I) is the measure of the magnetisation of a magnetized specimen. It is defined as the magnetic moment per unit volume.

$$I = M / V \text{ weber / metre}^2$$

Magnetic field intensity (or) strength (H)

Magnetic field intensity at any point in a magnetic field is the force experienced by unit north pole placed at that point.

It is denoted by H and its unit is Newton per weber or ampere turns per metre (A/m).

Magnetic permeability (μ)

Magnetic permeability of a substance measure the degree to which the magnetic field can penetrate through the substance.

It is found that magnetic flux density (B) is directly proportional to the magnetic field strength (H)

$$B \propto H$$
$$B = \mu H$$

Where μ is a constant of proportionality and it is known as permeability or absolute permeability of the medium.

$$\mu = B / H$$

Hence, the permeability of a substance is the ratio of the magnetic flux density (B) inside the

substance to the magnetic field intensity (H).

Absolute permeability

Absolute permeability of a medium or material is defined as the product of permeability of free space (μ_0) and the relative permeability of the medium (μ_r)

$$\mu = \mu_0 \times \mu_r$$

Relative permeability of medium (μ_r)

Relative permeability of a medium is defined as the ratio between absolute permeability of a medium to the permeability of a free space

$$\mu_r = \mu / \mu_0$$

Magnetic susceptibility (χ)

Magnetic susceptibility (χ) of a specimen magnetized in a magnetic field.

It is the ratio of intensity of magnetisation (I) induced in it to the magnetizing field (H).

$$\chi = I / H$$

Retentivity (or) Remanence

When the external magnetic field is applied to a magnetic material is removed, the magnetic material will not loss its magnetic property immediately. There exists some residual intensity of magnetization in the specimen even when the magnetic field is cut off. This is called residual magnetism (or) retentivity.

Coercivity

The residual magnetism can be completely removed from the material by applying a reverse magnetic field. Hence coercivity of the magnetic material is the strength of reverse magnetic field ($-H_c$) which is used to completely demagnetize the material.

2. ORIGIN OF MAGNETIC MOMENT AND BOHR MAGNETON

a. Origin of magnetic moment

Any matter is basically made up of atoms. The property of magnetism exhibited by certain materials with the magnetic property of its constituent atoms. We know that electrons in an atom revolve around the nucleus in different orbits.

Basically there are three contributions for the magnetic dipole moment of an atom.

The orbital motions of electrons (the motion of electrons in the closed orbits around the nucleus) are called orbital magnetic moment.

Spin motion of the electrons (due to electron spin angular momentum) is called spin magnetic moment.

The contribution from the nuclear spin (due to nuclear spin angular momentum) is nearly 10^3 times smaller than that of electron spin; it is not taken into consideration.

b. Bohr Magneton

The magnetic moment contributed by an electron with angular momentum quantum number $n = 1$ is known as Bohr Magneton.

3. DIFFERENT TYPES OF MAGNETIC MATERIALS

DIAMAGNETIC MATERIALS

Diamagnetism is exhibited by all the materials. The atoms in the diamagnetic materials do not possess permanent magnetic moment.

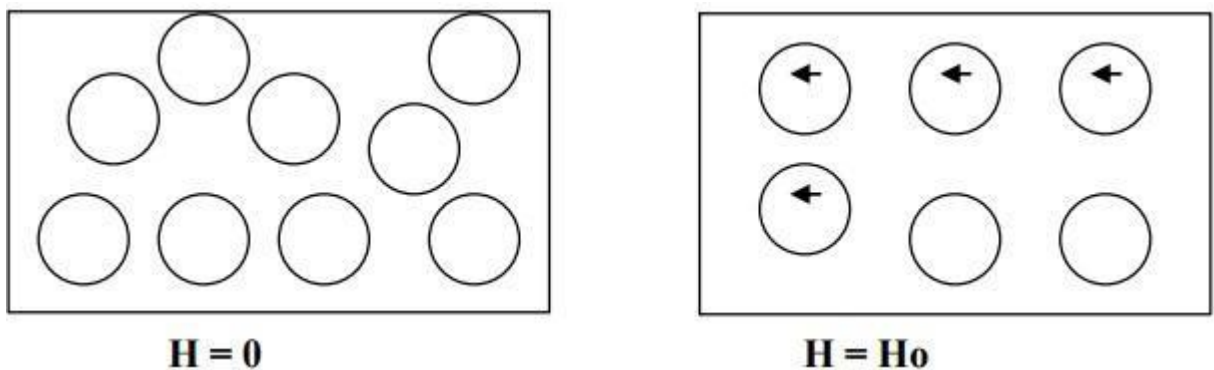
However, when a material is placed in a magnetic field, the electrons in the atomic orbits tend to counteract the external magnetic field and the atoms acquire an induced magnetic moment.

As a result, the material becomes magnetized. The direction of the induced dipole moment is opposite to that of externally applied magnetic field. Due to this effect, the material gets very weakly repelled, in the magnetic field. This phenomenon is known as diamagnetism.

When a magnetic field H_0 is applied in the direction shown in fig., the atoms acquire an induced magnetic moment in the opposite direction to that of the field.

The strength of the induced magnetic moment is proportional to the applied field and hence magnetization of the material varies directly with the strength of the magnetic field.

The induced dipoles and magnetization vanish as soon as the applied field is removed.

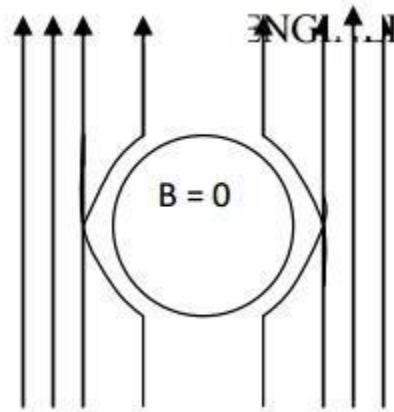
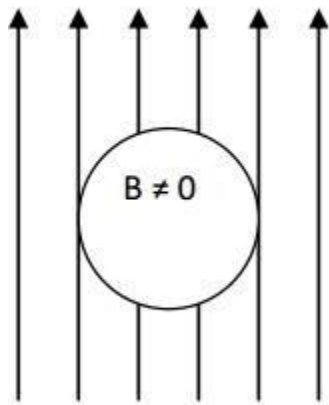


Properties of diamagnetic material

Diamagnetic magnetic material repels the magnetic lines of force. The behaviour of diamagnetic material in the presence of magnetic field.

There is no permanent dipole moment. Therefore, the magnetic effects are very small.

The magnetic susceptibility is negative and it is independent of temperature and applied magnetic field strength.

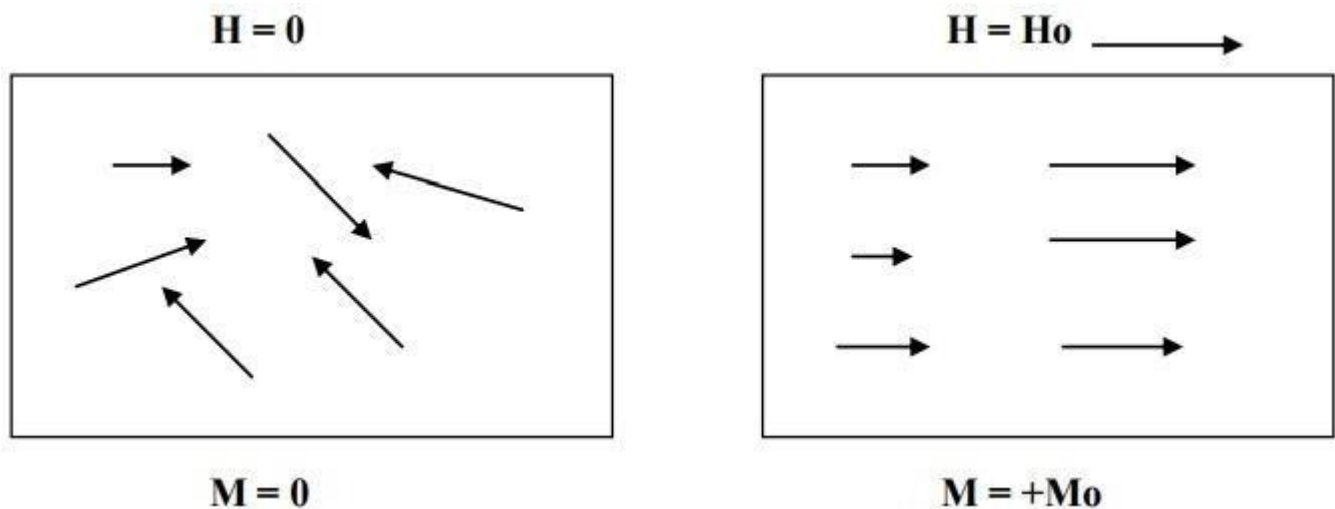


PARAMAGNETIC MATERIALS

In certain materials, each atom or molecule possesses a net permanent magnetic moment (due to orbital and spin magnetic moment) even in the absence of an external magnetic field.

The magnetic moments are randomly oriented in the absence of external magnetic field. Therefore the net magnetic moment is zero, and hence the magnetization of the material is zero.

But, when an external magnetic field is applied, the magnetic dipoles tend to align themselves in the direction of the magnetic field and the material becomes magnetized. As shown in fig. This effect is known as paramagnetism.



Thermal agitation disturbs the alignment of the magnetic moments. With an increase in temperature, the increase in thermal agitation tends to randomize the dipole direction thus leading to a decrease in magnetization.

This indicates that the paramagnetic susceptibility decreases with increases in temperature. It is noted that the paramagnetic susceptibility varies inversely with temperature.

$$\chi \propto \frac{1}{T} \quad \chi = \frac{C}{T}$$

This is known as Curie law of paramagnetism and C is a constant called Curie constant.

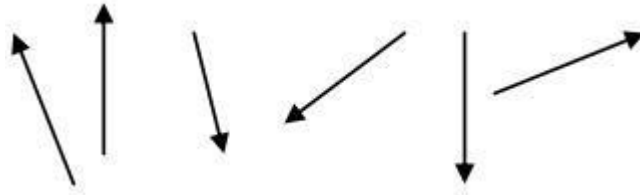
Properties of paramagnetic materials

Paramagnetic materials attract magnetic lines of force. They possess permanent dipole moment.

The susceptibility is positive and depend on temperature is given by

$$\chi = \frac{C}{T}$$

The spin alignment is shown in fig.



Example- Manganous sulphate, ferric oxide, ferrous sulphate, nickel sulphate, etc.

FERROMAGNETIC MATERIALS

Certain materials like iron, cobalt, nickel and certain alloys exhibit high degree of magnetization. These materials show spontaneous magnetization. (i.e) they have small amount of magnetization even in the absence of external magnetic field.

This indicates that there is strong internal field within the material which makes atomic magnetic moments with each other. This phenomenon is known as ferromagnetism.

Properties of ferromagnetic materials:

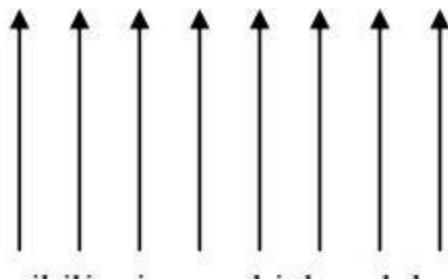
All the dipoles are aligned parallel to each other due to the magnetic interaction between the two dipoles.

They have permanent dipole moment. They are strongly attracted by the magnetic field.

They exhibit magnetization even in the absence of magnetic field. This property of ferromagnetic material is called as spontaneous magnetization.

They exhibit hysteresis curve.

On heating, they lose their magnetization slowly. The dipole alignment is shown in fig.



The susceptibility is very high and depends on the temperature. It is given by

$$\chi = C / T - \theta \text{ [for } T > \theta; \text{ paramagnetic behaviour; for } T < \theta; \text{ ferromagnetic behaviour]}$$

Where C is the Curie constant and θ is the paramagnetic Curie temperature.

ANTIFERROMAGNETIC MATERIALS

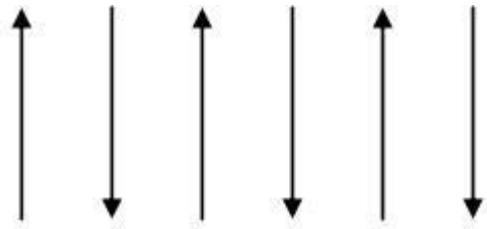
Antiferromagnetic materials are magnetic materials which exhibit a small positive susceptibility of the order of 10^{-3} to 10^{-5} .

In antiferromagnetic materials, the susceptibility increases with increasing temperature and it reaches maximum at a certain temperature called Neel Temperature, T_N .

With further increase in temperature, the material reaches the paramagnetic state. The material is antiferromagnetic below T_N .

Properties of antiferromagnetic materials

The electron spin of neighboring atoms are aligned antiparallel. (i.e) the spin alignment is antiparallel.



Antiferromagnetic susceptibility is mainly depends on temperature.

The susceptibility of the antiferromagnetic material is small and positive. It is given by

$$\chi = C / T + \theta \quad \text{when } T > T_N$$

$$\chi \propto T \quad \text{when } T < T_N$$

The susceptibility initially increases slightly with the temperature and beyond Neel temperature, the susceptibility decreases with temperature.

FERRIMAGNETIC MATERIALS

Properties of ferrites

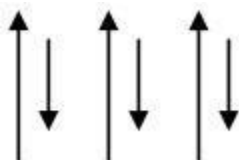
Ferrites have net magnetic moment.

Above Curie temperature, it becomes paramagnetic, while it behaves ferromagnetic material below Curie temperature.

The susceptibility of ferrite is very large and positive. It is temperature dependent and is given by

$$\chi = C / T \pm \theta \quad \text{for } T > T_N$$

Spin alignment is antiparallel of different magnitudes as shown fig.



Mechanically it has pure iron character. They have high permeability and resistivity.

They have low eddy current losses and low hysteresis losses.

4. FERROMAGNETISM

The materials which have finite value of magnetization even if the external magnetic field is absent are called ferromagnetic materials. This phenomenon is called ferromagnetism. The ferromagnetic materials exhibit high degree of magnetization.

Explanation

In a ferromagnetic material, the magnetic interactions between any two dipoles align themselves parallel to each other. Ferromagnetism arises due to the special form of interaction called exchange coupling between adjacent atoms. This exchange coupling is favourable for spin alignment and they couple their magnetic moments together in rigid parallelism.

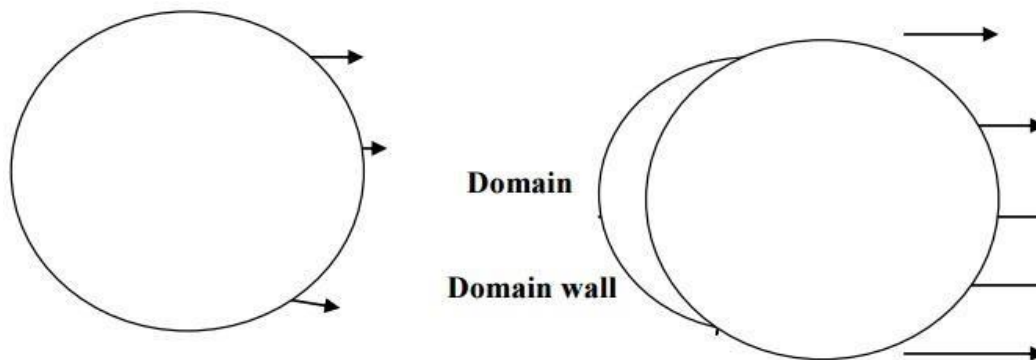
A ferromagnetic material exhibits ferromagnetic property below a particular temperature called ferromagnetic Curie temperature (T_c). Above T_c it behaves as a paramagnetic material.

5. DOMAIN THEORY OF FERROMAGNETISM

We can observe that ferromagnetic materials such as iron do not have magnetization unless they have been previously placed in an external magnetic field. But according to Weiss theory, the molecular magnets in the ferromagnetic material are said to be aligned in such a way that they exhibit magnetization even in the absence of an external magnetic field. This is called spontaneous magnetization. (i.e.) it should have some internal magnetization due to quantum exchange energy.

According to Weiss hypothesis, a single crystal of ferromagnetic material is divided into a large number of small regions called domains. These domains have spontaneous magnetization due to the parallel alignment of spin magnetic moments in each atom. But the direction of spontaneous magnetization varies from domain to domain and is oriented in such a way that the net magnetization of the specimen is zero.

The boundaries separating the domains are called domain walls. These domain walls are analogous to the grain boundaries in a polycrystalline material.



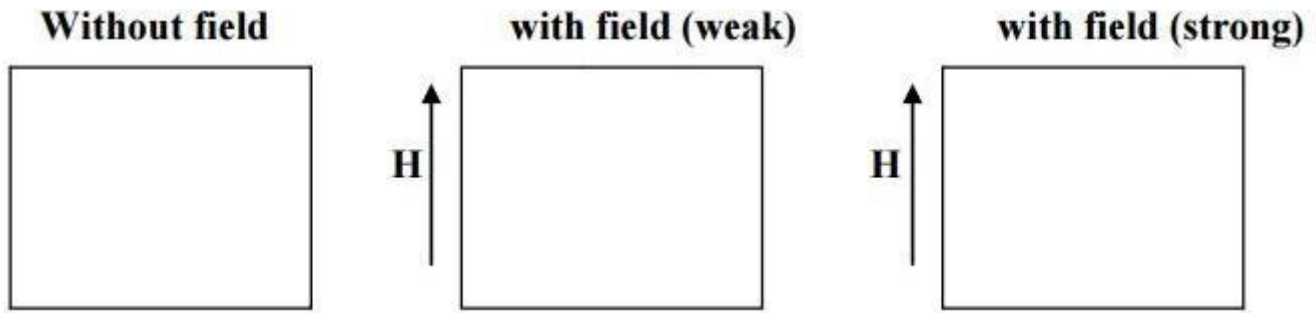
a. DOMAIN MAGNETIZATION

Now when the magnetic field is applied, then the magnetization occurs in the specimen by two ways:
 By movement of domain walls By rotation of domain walls **movement of domain walls**

The movement of domain walls takes place in weak magnetic fields. Due to this weak field applied to the specimen, the magnetic moment increases and hence the boundary of domains is displaced, so that the volume of the domains changes as shown in the figure.

By rotation of domain walls

The rotation of domain walls takes place in strong magnetic fields. When the external field is high, then the magnetization changes by means of rotation of the direction of magnetization towards the direction of the applied field as shown in the figure.



b. ENERGIES INVOLVED IN DOMAIN GROWTH

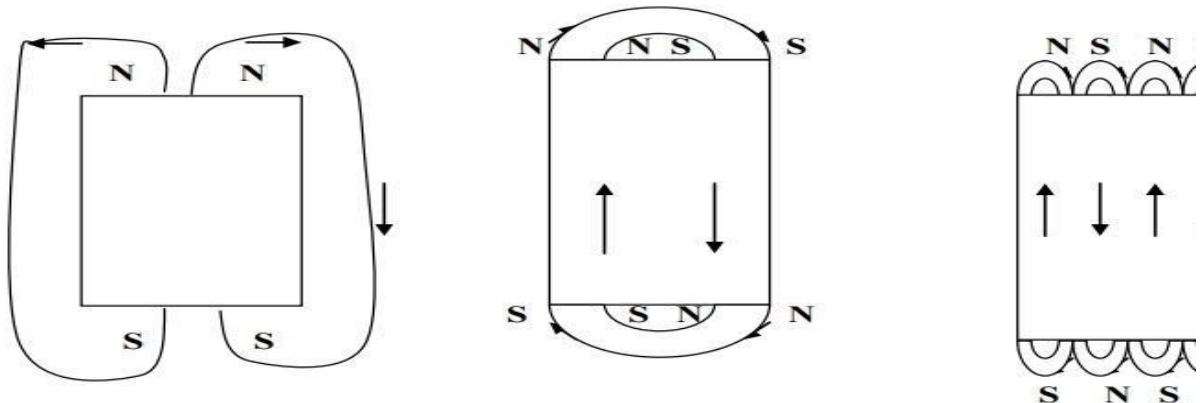
To study the domain structure clearly, we must know four types of energy involved in the process of domain growth. They are

Exchange energy Anisotropy energy Domain wall energy Magneto-strictive energy

Exchange energy (or) magnetic field energy (or) magneto-static energy

The interacting energy which makes the adjacent dipoles to align themselves is known exchange energy (or) magnetic field energy. The exchange energy has established a single domain in a specimen of ferromagnetic and it is shown in fig.

It is the energy required in assembling the atomic magnets in a single domain and this work done is stored as potential energy.



Anisotropy energy

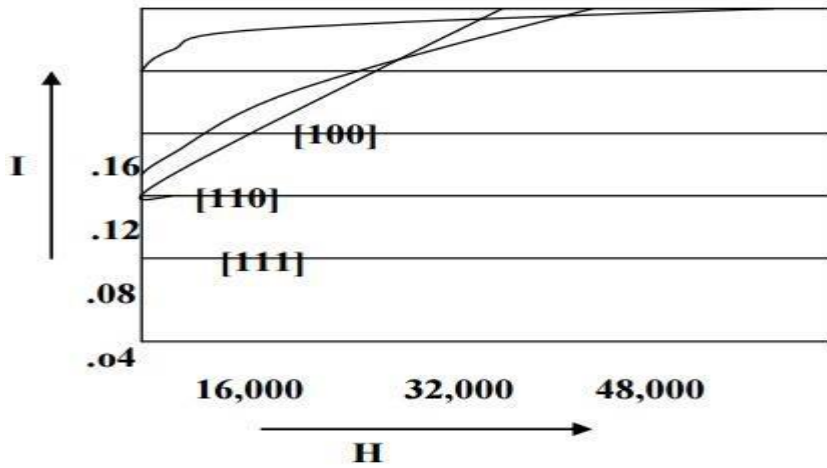
In ferromagnetic crystals there are two direction of magnetization. Easy direction

Hard direction

In easy direction of magnetization, weak field can be applied and in hard direction of magnetization, strong field should be applied. For producing the same saturation magnetization along both hard and easy direction, strong fields are required in the hard direction than the easy direction.

For example in iron easy direction is [100], medium direction is [110] and the hard direction is [111] and it is shown in fig. From the fig we can see that very strong field is required to produce magnetic saturation in hard direction [111] compared to the easy direction [100].

Therefore the excess of energy required to magnetize the specimen along hard direction over that required to magnetize the specimen along easy direction is called crystalline anisotropy energy.



Domain wall energy (or) Bloch wall energy

Domain wall is a transition layer which separates the adjacent domains, magnetized in different directions. The energy of domain wall is due to both exchange energy and anisotropy energy.

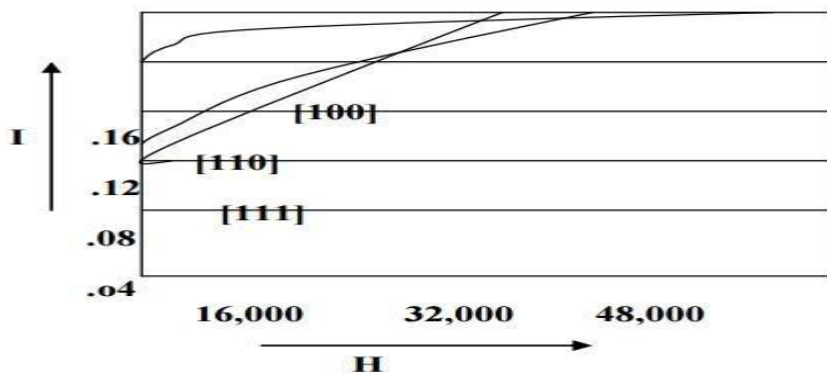
Based on the spin alignment, two types of domain walls may arise, namely Thick wall
Thin wall

Thick wall

When the spin at the boundary are misaligned if the direction of the spin changes gradually as shown in fig, it leads to a thick domain wall. Here the misalignments of spins are associated with exchange energy.

Thin wall

When the spin at the boundaries changes abruptly, then the anisotropy energy becomes very less. Since the anisotropy energy is directly proportional to the thickness of the wall, this leads to a thin Bloch wall.



Magnetostrictive energy

When the domains are magnetized in different directions, they will either expand (or) shrink.

Therefore there exists a deformation (i.e) change in dimension of the material, when it is magnetized.

This phenomenon is known as magnetostriction and the energy produced in this effect is known as magnetostriction energy.

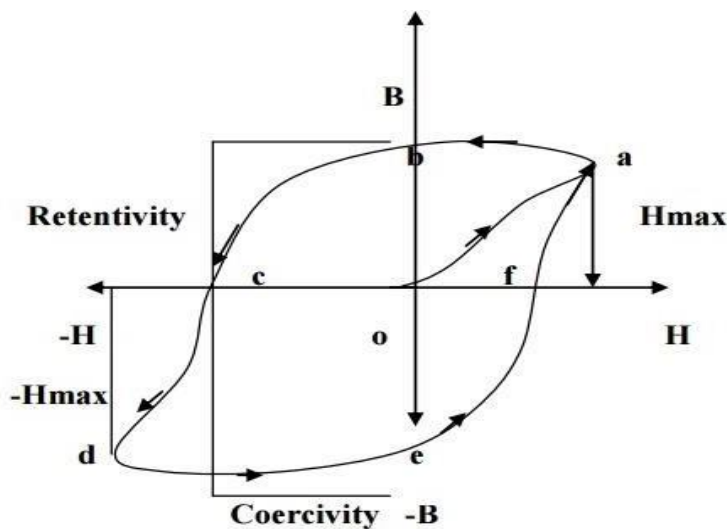
The deformation is different along different crystal directions and the change in dimension

depends upon the nature of the material.

c. EXPLANATION OF HYSTERESIS BASED ON DOMAIN THEORY Hysteresis

When a ferromagnetic material is made to undergo through a cycle of magnetization, the variation of magnetic induction (B) with respect to applied field (H) can be represented by a closed hysteresis loop (or) curve. (i.e) it refers to the lagging of magnetization behind the magnetizing field.

If magnetizing field (H) is applied to a ferromagnetic material and if H is increases to Hmax the material acquires magnetism. So the magnetic induction also increases, represented by oa in the fig.



Now if the magnetic field is decreased from Hmax to zero, the magnetic induction will not fall rapidly to zero, but falls to 'b' rather than removed, the material still acquire some magnetic induction (ob) which is so called residual magnetism or retnivity.

Now, to remove the residual magnetism, the magnetic field strength is reversed and increased to – Hmax represented as 'oc' so called coercivi-H) is reduced to zero and the corresponding curve 'de' is obtai curve 'efa' is obtained.

We know when the ferromagnetic material is subjected to external field, there is an increase in the value of the magnetic moment due to two process. The moment of domain walls Rotation of domain walls.

When small external field is applied, the domains walls displaced slightly in the easy direction of magnetization. This gives rise to small magnetization corresponding to the initial portion of the hysteresis curve (OA) as shown in fig.

Now of the field is removed, then the domains returns to the original state, and is known as reversible domains.

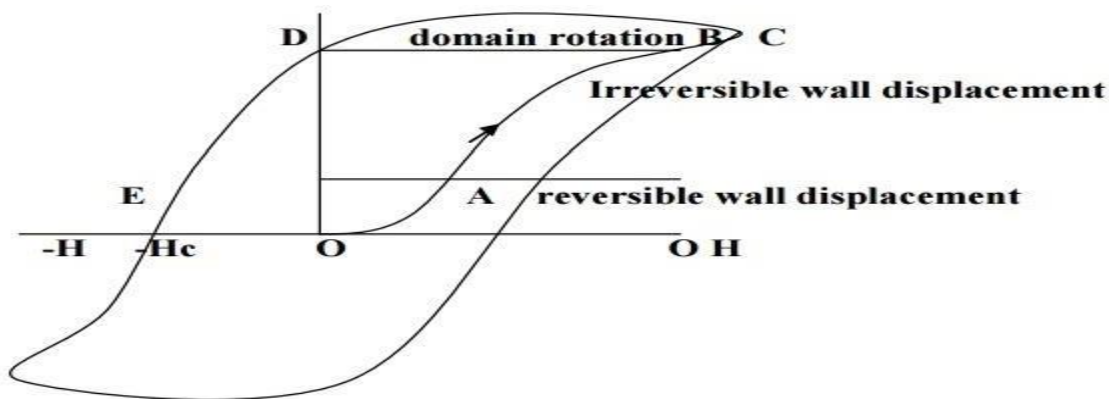
When the field is increased, large numbers of domains contribute to the magnetization and thus the magnetization increases rapidly with H.

Now, even when the field is removed, because of the displacement of domain wall to a very large distance, the domain boundaries do not come back to their original position. This process is indicating as AB in fig and these domains are called irreversible domains.

Now, when the field is further increased, the domains starts rotating along the field direction and the anisotropic energy stored in the hard direction, represented as BC in the fig.

Thus the specimen is said to attain the maximum magnetization. At this position, even when the field is removed the material possesses maximum magnetization, called residual magnetism or retentivity, represented by OD in fig.

Actually after the removal of external field, the specimen will try to attain the original configuration by the movement of domain wall. But this movement is stopped due to presence of impurities, lattice imperfections etc. therefore to overcome this; a large amount of reverse magnetic field is applied to the specimen. The amount of energy spent to reduce the magnetization to zero is called coercivity represented by OE in the fig.



It is the loss of the energy in taking a ferromagnetic specimen through a complete cycle of magnetization and the area enclosed is called hysteresis loop.

6. SOFT AND HARD MAGNETIC MATERIALS

Depending upon the direction of magnetization by external field, and the area of hysteresis, magnetic can be classified into two types as,

TYPES OF MAGNETIC MATERIALS

Magnetic materials are classified into two types. Soft magnetic materials .
Hard magnetic material

Soft magnetic materials:

Materials which are easy to magnetize and demagnetize are called soft magnetic materials.

Example –pure iron, cast iron, carbon steel, silicon steel, mumetal.

Hard magnetic materials:

Materials which retain their magnetism and are difficult to demagnetize are called hard magnetic materials.

Example –tungsten steel, cobalt steel, alini, alnico, hypernic **Difference between soft and hard magnetic materials**

Difference between soft and hard magnetic materials

s.no	Soft magnetic materials	Hard magnetic materials
1.	The magnetic materials can be easily magnetize and demagnetize.	The magnetic materials can not be easily magnetize and demagnetize.
2.	The have high permeability.	The have low permeability.
3.	Magnetic energy stored is not high.	Magnetic energy stored is high.
4.	Low hysteresis loss due to small hysteresis loop area.	Large hysteresis loss due to hysteresis loop area.
5.	Coercivity and retentivity are small.	Coercivity and retentivity are large.
6.	The eddy current loss is small due to its high resistivity.	The eddy current loss is high due to low resistivity.
7.	The domain walls are easy to move.	The movement of domain wall must be prevented.
8.	They are used in electric motor, generators, transformers, relays, telephone receivers, radar.	They are used in loud speakers and electrical measuring instruments.

Soft magnetic materials:

1. The magnetic materials can be easily magnetize and demagnetize.
2. The have high permeability.
3. Magnetic energy stored is not high.
4. Low hysteresis loss due to small hysteresis loop area.
5. Coercivity and retentivity are small.
6. The eddy current loss is small due to its high resistivity.
7. The domain walls are easy to move.
8. They are used in electric motor, generators, transformers, relays, telephone receivers, radar.

Hard magnetic materials

1. The magnetic materials can not be easily magnetize and demagnetize.
2. The have low permeability.
3. Magnetic energy stored is high.
4. Large hysteresis loss due to large hysteresis loop area.
5. Coercivity and retentivity are large.
6. The eddy current loss is high due to its low resistivity.
7. The movement of domain wall must be prevented.
8. They are used in loud speakers and electrical measuring instruments.

7. ENERGY PRODUCT Definition

The product of residual magnetic induction (Br) and coercivity(Hc) is called energy product or BH product. It is the important quantity to design powerful permanent magnets. It gives the maximum amount of energy stored in the specimen.

Explanation

The energy required to demagnetize a permanent magnet is given by the area of the hysteresis loop between B_r and H_c . The maximum value of this area $B_r H_c$ is called the energy product.

At C and D the energy product is zero because at C, H value is zero and D, B value is zero. The area occupied by the largest rectangle in demagnetizing curve gives the maximum (BH) value.

The energy product is large for permanent magnets. This value is very much useful to analyze whether the material can be used for magnetic recording.

8. FERRIMAGNETIC MATERIALS - FERRITES Ferrites

Ferrites are components of iron oxide with oxides of other components.

The general chemical formula is $X^{2+} Fe^{23+} O_4^{2-}$, where (X^{2+}) is a divalent metal ion such as Fe^{2+} , Mg^{2+} , Ni^{2+} , Co^{2+} , Mn^{2+}

a. STRUCTURE OF FERRITES

Generally there are two types of structures present in the ferrites. They are Regular spinel
Inverse spinel

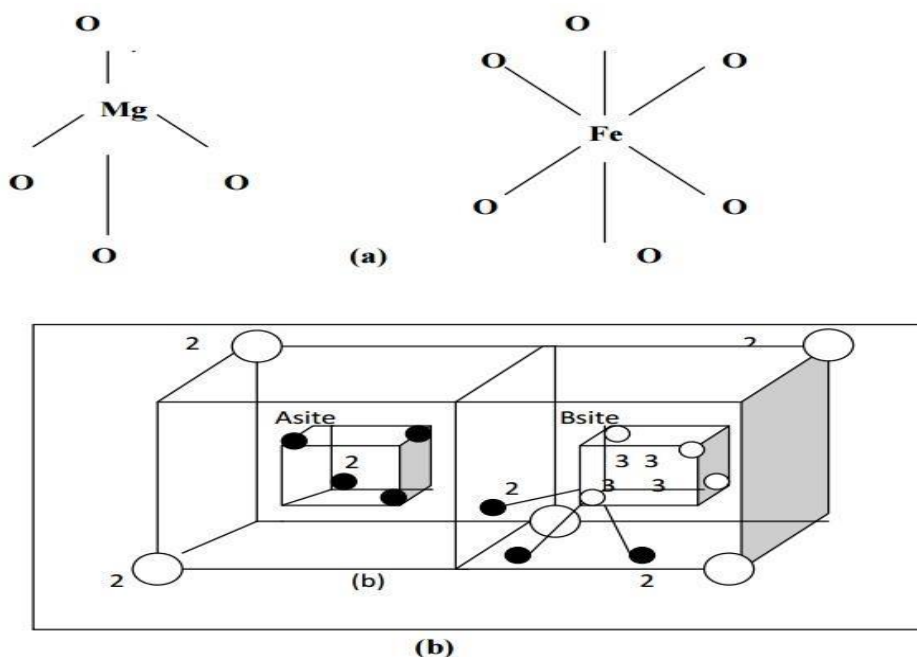
Regular spinel

In regular spinel structure, each divalent metal ion is surrounded by four O^{2-} ions in a tetrahedral fashion.

For example in $Mg^{2+} Fe^{23+} O_4^{2-}$, the structure of Mg^{2+} is given in the fig (a) and it is called A site.

Each Fe^{3+} (trivalent metal ion) is surrounded by six O^{2-} ions and forms an octahedral fashion as shown in fig (a). Totally there will be 16 such octahedral sites in the unit cell. This is indicated by B site.

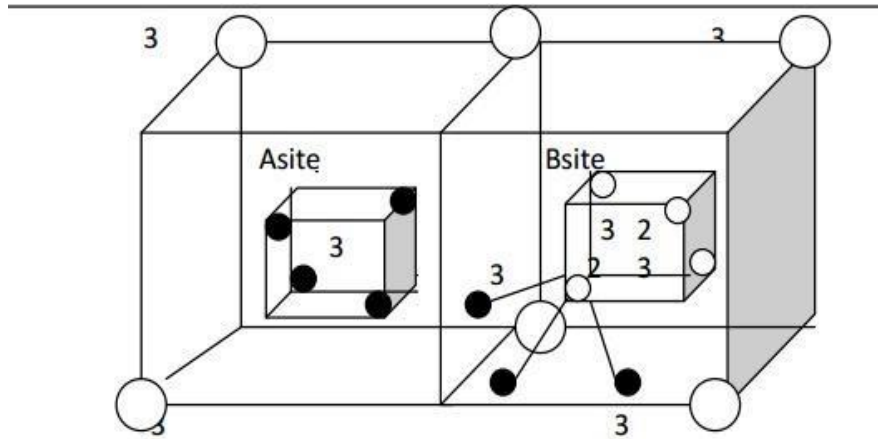
Thus in regular spinel, each divalent metal ion (Mg^{2+}) exists in tetrahedral form (A site) and each trivalent metal ion (Fe^{3+}) exists in an octahedral form (B site). Hence the sites A and B combine together to form a regular spinel ferrite structure as shown in fig (b).



Inverse spinel

In this type, we consider the arrangement of ions of a single ferrous ferrite molecule $\text{Fe}^{3+} [\text{Fe}^{2+} \text{Fe}^{3+}] \text{O}_4^{2-}$. A Fe^{3+} ion (trivalent) occupies all A sites (tetrahedral) and half of the B sites (octahedral) also.

Thus the left out B sites will be occupied by the divalent (Fe^{2+}). The inverse spinel structure is shown in fig (c).



b. PREPARATION

They have the general chemical composition $\text{A}^{2+} \text{Fe}^{23+} \text{O}_4^{2-}$ where A^{2+} represent a divalent metal ion like Zn^{2+} , Mg^{2+} , etc. Ferrites are prepared by sintering a mixture of various metallic oxides as follows.

1. Suitable of A^{2+} and $\text{Fe}^{23+} \text{O}_4^{2-}$ in proper proportions are mixed using water or kerosene.
2. The mixing is done in a blender for several hours. It is filtered.
3. The filtered material is dried in a hot oven and is then crushed.
4. Next mixture, is pre-sintered in a furnace at 9000c to 11000c for a period of three to fifteen hours, in an air atmosphere or nitrogen atmosphere.
5. The pre-sintered material is then ground into a fine powder and mixed with a binder such as paraffin wax and a solvent such as water.
6. The mixture is then pressed into the desired shapes by using dies.
7. The last step in the process is to place the ferrite in proper vessel in a furnace and heat it to about $1100\text{to } 14000\text{c}$. The binder then evaporates. It is cooled in a controlled manner.

PROPERTIES OF FERRITES

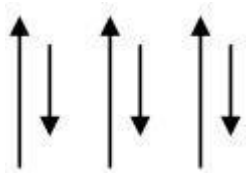
Ferrites have net magnetic moment.

Above Curie temperature, it becomes paramagnetic, while it behaves ferromagnetic material below Curie temperature.

The susceptibility of ferrite is very large and positive. It is temperature dependent and is given by

$$\chi = C / T \pm \theta \quad \text{for } T > T_N$$

Spin alignment is antiparallel of different magnitudes as shown fig.



Mechanically it has pure iron character. They have high permeability and resistivity. They have low eddy current losses and low hysteresis losses.

Advantages

1. Efficiency is high and cost is low.
2. They have low eddy current losses and low hysteresis losses.
3. Easy to manufacture with great uniformity.
4. They occupies low volume.

Disadvantages

1. The main disadvantage of bubble memory is the requirement of a high recording time for
2. storing and retrieving the data than the charge coupled device (CCD).
3. It requires the interface circuits.
4. When compared with charge coupled device (CCD) memory the magnetic bubble memory has slow access speed.

Applications

They are used to produce ultrasonic waves by magnetostriction principle. Ferrites are used in audio and video transforms.

Ferrite rods are used in radio receivers to increase the sensitivity. They are also used in power limiting and harmonic generation. They are used in computers and data processing circuits.

Ferrites are used in paramagnetic amplifiers so that the input can be amplified with low noise figures.

DIELECTRIC MATERIALS

DIELECTRICS

Solids which have an energy gap of three eV or more are termed as insulators. In these materials, it is almost not possible to excite the electrons from the valence band to conduction band by an applied field. Generally dielectrics are also called as insulators, thereby poor conductors of electricity. However they allow movement of some electrons at abnormally high temperatures, causing a small flow of current. Dielectrics are non-metallic materials of high specific resistance ρ , negative temperature coefficient of resistance $(-\alpha)$, and large and insulation resistance. Insulation resistance will be affected by moisture, temperature, applied electric field and age of dielectrics.

Dielectric materials are electrically non-conducting materials such as glass, ebonite, mica, rubber, wood and paper. All dielectric materials are insulating materials. The difference between a dielectric and an insulator lies in their applications.

If the main function of non-conducting material is to provide electrical insulation, then they are called as insulator. On the other hand, if the main function of non-conducting material is to store electrical charges then they are called as dielectrics.

PROPERTIES

Generally, the dielectrics are non-metallic materials of high resistivity. They have a very large energy gap (more than 3eV).

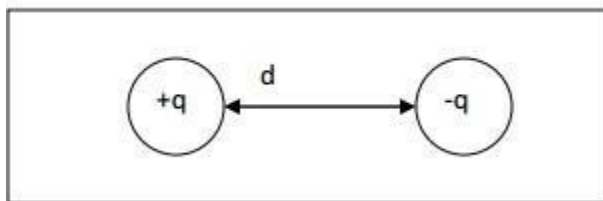
All the electrons in the dielectrics are tightly bound to their parent nucleus.

As there are no free electrons to carry the current, the electrical conductivity of dielectrics is very low.

They have negative temperature coefficient of resistance and high insulation resistance.

FUNDAMENTAL DEFINITIONS AND PROPERTIES ELECTRIC DIPOLE

A system consisting of two equal and opposite charges $+q$, $-q$ separated by a distance (d) is called an electric dipole.



DIPOLE MOMENT (M)

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

Dipole moment = qd (coulomb-metre)

PERMITTIVITY (E)

The permittivity represents the dielectric property of a medium. It indicates easily polarisable nature of material. Its unit is farad/metre

DIELECTRIC CONSTANT (

A dielectric characteristic of a material is determined by its dielectric constant. It is a measure of polarisation of the dielectrics.

Definition

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

Dielectric constant = Absolute permittivity(ϵ)/Permittivity of free space (ϵ_0)

$\epsilon_r = \epsilon_0 / \epsilon$

POLARIZATION

Definition

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

POLARISABILITY (A)

It is found that the average dipole moment field (E). It is found that the average dipole moment field (E). μ

$$\alpha E$$

$$\text{Or } \mu = \alpha E$$

Where (α) is the polarisability. $\alpha = \mu/E$

Polarisability is defined as the ratio of average dipole moment to the electrical field applied.

Its unit is farad m^2 .

Polarization vector

It is defined as the average dipole moment per unit volume of a dielectric. If N is the number atoms per unit volume of a dielectric and (μ) is average dipole moment per atom, then

$$\vec{P} = N\mu \quad (\text{coulomb /m}^2)$$

VARIOUS POLARIZATION MECHANISMS INVOLVES IN DIELECTIC

Dielectric polarization is the displacement of charged particles under the action of the external electric field. There are number of devices based on this concept. Those devices are rectifiers, resonators, amplifiers and transducers, which converts electrical energy in to other forms of energy.

Dielectric polarization occurs due to several microscopic mechanisms. Electronic polarization

Ionic polarization Orientational polarization Space-charge polarization

ELECTRONIC POLARIZATION

Electronic polarization occurs due to displacement of positively charged nucleus and negatively charged electrons of an atom in the opposite directions on the application of an electric field. This will result in the creation of dipole moment in the dielectric.

Dipole moment (μ) is proportional to the electric field strength (E). $\mu \propto E$

$$\mu = \alpha_e E$$

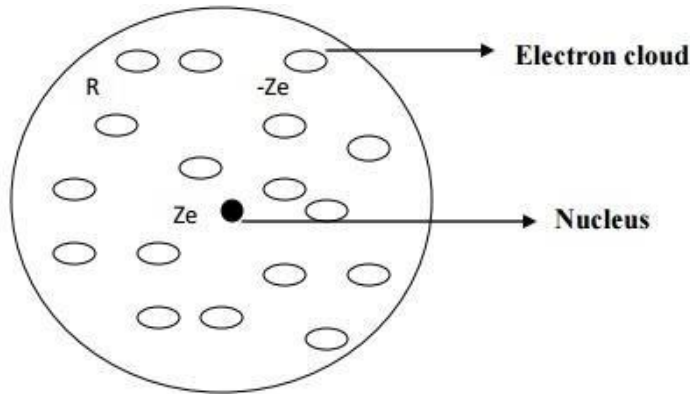
Where (α_e) is proportionality constant and it is known as electronic polarizability.

Electronic polarization takes place in almost all dielectrics.

Calculation of electronic polarizability

WITHOUT ELECTRIC FIELD

Consider an atom of a dielectric material of nuclear charge Ze , where Z is the atomic number. The electrons of charge $(-Ze)$ are distributed uniformly throughout the atom (sphere) of radius R as shown in fig.



The centres of the electron cloud and the positive nucleus are at the same point and hence there is no dipole moment.

Negative charge density of an atom of radius R is given by

$$\rho = \frac{\text{Total negative charge}}{\text{Volume of the atom}} = \frac{-Ze}{\frac{4}{3} \pi R^3}$$

i.e)

$$\rho = \frac{3}{4} \left[\frac{-Ze}{\pi R^3} \right] \longrightarrow (1)$$

WITH ELECTRIC FIELD

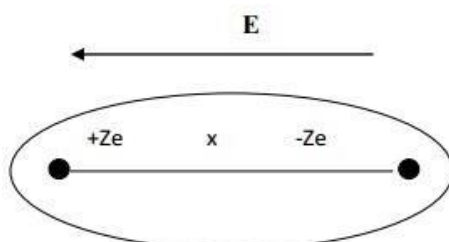
When the atom of the dielectric is placed in an electric field of strength E , two phenomenons occur.

Lorentz force (due to electric field) will tend to move the nucleus and electron cloud of that atom from their equilibrium positions. The positive nucleus will move towards the field direction and the electron cloud will move in the opposite direction of the field as shown in fig.

After separation, an attractive coulomb force arises between the nucleus and the electron cloud which will tend to maintain the original equilibrium position.

The electron cloud and the nucleus move in opposite directions and they are separated by a distance x , where there is a formation of electric dipole in the atom.

When these two forces equal and opposite, there will be a new equilibrium between the nucleus and the electron cloud of the atom.



Lorentz force between the nucleus and the electron $F_L = \text{charge} \times \text{electrical field}$
 $= ZeE$ ----- (2)

Coulomb attractive force between the nucleus and the electron cloud being separated at a distance x ,

$$F_C = \frac{1}{4\pi\epsilon_0} \frac{Q_p Q_e}{x^2}$$

Charge \times Total negative charges enclosed in
 The sphere of radius R

$$= \frac{\text{Charge} \times \text{Total negative charges enclosed in The sphere of radius } R}{(4\pi\epsilon_0 x^2)} \longrightarrow (3)$$

Total number of negative charges enclosed

In the sphere of radius $x = \text{charge density} \times \text{volume of the sphere of Radius } x$

$$= - [3/4] x \frac{Ze}{\pi x^3} \frac{4\pi}{3} R^3$$

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

Total positive charge of an atom present in the sphere of radius x , $Q_p = + Ze$

Substituting equation 4 in 3 we have

$$F_C = Ze \frac{- Ze [x^3 / R^3]}{(4\pi\epsilon_0 x^2)}$$

$$F_C = - \frac{Z^2 e^2 x}{(4\pi\epsilon_0 R^3)} \longrightarrow (5)$$

At equilibrium, Coulomb force and Lorentz must be equal and opposite.

$$F_L = - F_C$$

Substituting for F_L and F_C from equation 2 and 5 we have

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

$$ZeE = \left(\frac{Z^2 e^2 x}{4\pi\epsilon_0 R^3} \right)$$

$$E = \frac{Ze x}{4\pi\epsilon_0 R^3}$$

$$\text{Or } x = \frac{E (4\pi\epsilon_0 R^3)}{Ze} \longrightarrow (6)$$

From the definition of dipole moment, induced dipole moment (μ_{ind}) is given by

$\mu_{ind} = \text{magnitude of charge} \times \text{displacement} \mu_{ind} = Ze x$

and dipole moment in terms of polarizability,

$$\mu_{ind} = \alpha_e E \text{ ----- (7)}$$

Substituting the value of x from 6 in 7 we have

$$\mu_{ind} = \frac{Ze E (4\pi\epsilon_0 R^3)}{Ze}$$

$$\mu_{ind} = E (4\pi\epsilon_0 R^3) \longrightarrow (8)$$

On comparing equation 8 and 9, we have

$$\mu_{ind} = \alpha_e E$$

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

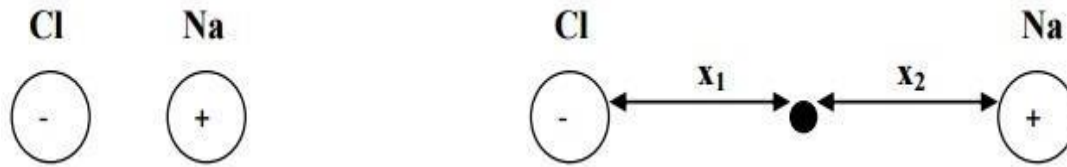
Electronic polarization is independent of temperature.

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

IONIC POLARIZATION

Ionic polarization is due to the displacement of cations (+ ve ions) and anions (- ve ions) in opposite directions. (e.g. NaCl crystal) by the influence of external field.

When an electric field (E) is applied on an ionic dielectric, there is shift of one ion with respect to another from their mean position. The positive ion displace in the direction of applied electric field through the distance x_1 . The negative ions displace in opposite direction trough the distance x_2 as shown in the fig.



We assume that there is one cation and one anion in each unit cell of that ionic crystal.

Hence, the net distance between two ions

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

When the ions are displaced from their mean position in their respective directions the restoring forces appear which tend to ions back to their mean position. The restoring force produced is proportional to the displacement.

For positive ion Restoring force $F \propto x$

$$\text{Or restoring force acting on positive ion } F = \beta_1 x_1 \text{----- (2)}$$

For negative ion

Restoring force $F \propto x_2$

$$\text{Or restoring force acting on negative ion } F = \beta_2 x_2 \longrightarrow \text{(3)}$$

Where β_1 and β_2 are restoring force constants which depend up on the masses of ions and angular frequency of the molecule in which ions are present.

If m is the mass of positive ion, M is the mass of negative ion and ω_0 is the angular frequency, then

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

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

Substituting for β_1 from equation 4 in equation 2, the restoring force for written as

$$F = m \omega_0^2 x_1 \longrightarrow \text{(6)}$$

We know that force $F = eE \longrightarrow \text{(7)}$

Equating 6 and 7, we get

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

or $x_1 = \frac{eE}{m \omega_0^2} \longrightarrow \text{(8)}$

Similarly for the negative ion we can write

or $x_2 = \frac{eE}{M \omega_0^2} \longrightarrow \text{(9)}$

Adding equations 8 and 9, we have

$$x = x_1 + x_2 \left[\frac{eE}{m \omega_0^2} + \frac{eE}{M \omega_0^2} \right] = \frac{eE}{\omega_0^2} \left[1/m + 1/M \right] \longrightarrow$$

The dipole moment is equal to the product of charge and distance of separation between the charges.

$$\mu = e X x \quad \longrightarrow \quad (11)$$

Substituting for x from equation 10 in equation 11, we have

$$\mu = e x \frac{eE}{\omega_0^2} \left(\frac{1}{m} + \frac{1}{M} \right)$$

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

But $\mu \propto E$ \longrightarrow (

$\mu = a_i E$ \longrightarrow (

Where (a_i) is the ionic polarizability of dielectric material

On comparing equation 12 and 13, we have

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

Conclusion

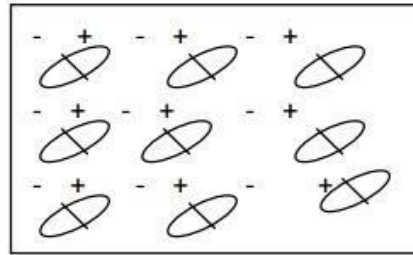
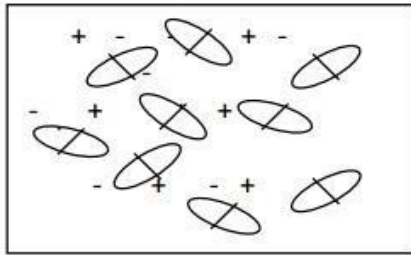
Ionic polarizability (a_i) is inversely proportional to the square of angular frequency of the ionic molecule. It is directly proportional to its reduced mass given by

$$\left(\frac{1}{m} + \frac{1}{M} \right)$$

It is independent of temperature.

ORIENTATIONAL POLARIZATION

Orientalional polarization takes place only in polar dielectrics. Polar dielectrics have molecules with permanent dipole moments even in the absence of external electric field.



When the polar dielectrics are subjected to external electric field, the molecular dipoles are oriented in the direction of electric field.

The contribution to polarization due to orientation of molecular dipoles is called orientational polarization.

Orientalional polarization depends upon temperature when the temperature is increased , thermal energy tends to disturb the alignment.

From the Langevin's theory of paramagnetism , net intensity of magnetization

$$= \frac{N\mu^2 B}{3kT}$$

Since the same principle can be applied to the application of electric field in dielectrics, we may write **Orientalional polarization, P_o** =

$$\text{Orientalional polarization, } P_o = \frac{N\mu^2 E}{3kT} \quad \longrightarrow \quad (1)$$

But, orientational polarization is proportional to applied field (E) and it is given by

$$P_o = \epsilon_0 E N\alpha \quad (2)$$

Comparing equations 1 and 2, we get

$$\alpha_o = \frac{\mu^2}{3kT}$$

Where (α_o) is orientational polarizability.

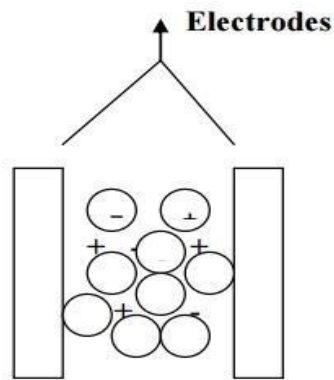
Conclusion

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

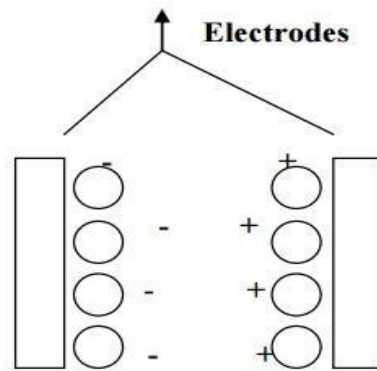
SPACE CHARGE POLARIZATION

Space-charge polarization occurs due to accumulation of charges at the electrodes or at the interfaces of multiphase dielectric material.

When such materials subjected to an electrical field at high temperature, the charges get accumulated as shown in fig. these charges create dipoles.



In the absence of an electric field



In the presence of an electric field

As a result, polarization is produced. This kind of polarization is known as space-charge polarization. Space-charge polarization is very small when compared to other polarization mechanisms and it is not common in most of the dielectrics.
e.g- ferrites and semiconductors.

TOTAL POLARIZATION $\alpha = \alpha_e + \alpha_i + \alpha_o$

Since the space-charge polarization is very small and it is negligible. Substituting the corresponding expressions, we have

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

We know that the total polarization $P = N E \alpha$

$$\alpha = N E \left[4\pi\epsilon_0 R^3 + \frac{e^2 E}{\omega_0^2} \left(\frac{1}{m} + \frac{1}{M} \right) + \frac{\mu^2}{3kT} \right]$$

This equation is known as Langevin –Debye equation

INTERNAL FIELD OR LOCAL FIELD DEFINITION

When a dielectric material is placed in an external electric field, it produces an induced dipole moment. Now, two fields are acting at any point inside dielectrics are

Macroscopic electrical field due to external electric field. Electrical field due to electric dipole moment.

These long range coulomb fields produced due to dipoles is known as internal field or local field. This internal field is responsible for polarization of each atom or molecule in the solid.

DERIVATION
LORENTZ METHOD TO FIND INTERNAL FIELD

The dielectric material is uniformly polarized by placing it in between two plates of parallel plate capacitor as shown in figure.

Assume an imaginary spherical cavity around an atom for which the internal field must be calculated at its centre. The internal field (E_{int}) at the atom site is considered to be made up of the following four components. E_1 , E_2 , E_3 and E_4 .

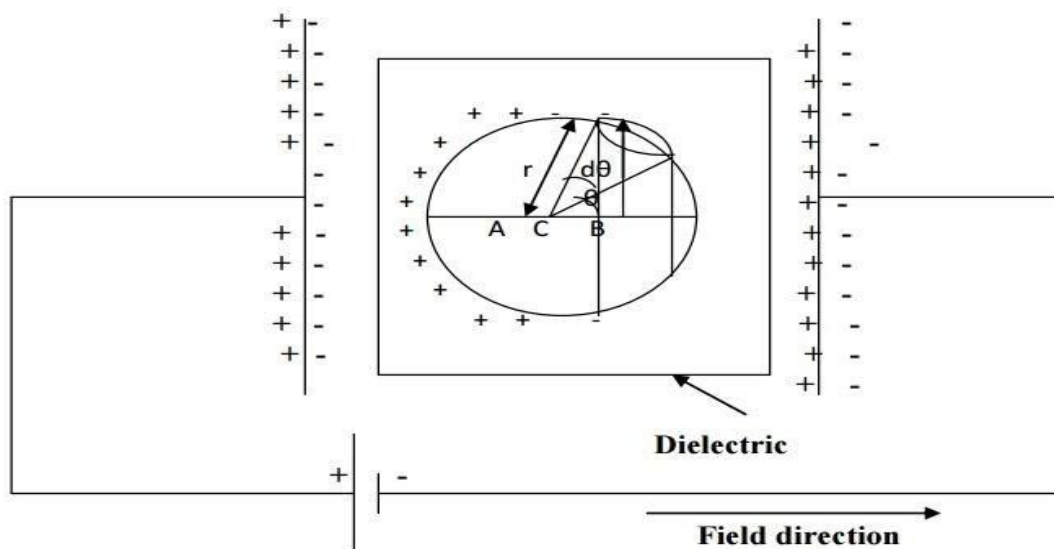
$E_{int} = E_1 + E_2 + E_3 + E_4$

Where E_1 –Electrical field due to charges on the plates of the capacitor

E_2 –Electric field due to polarized charges (induced charges) on the plane surface of the dielectric.

E_3 –Electric field due to polarized charges induced on the surface of the imaginary spherical cavity.

E_4 –Electric field due to permanent dipoles of atoms inside the spherical cavity considered.



Macroscopically we can take $E = E_1 + E_2$. i.e., the electrical field externally applied (E_1) and the electrical field induced on the plane surface of the dielectric (E_2) can be considered as a single electrical field.

If we consider a dielectric that is highly symmetric, the electrical field due to dipoles present inside the imaginary cavity will cancel out of each other. Therefore the electrical field due to permanent dipoles $E_4 = 0$

Now, the equation (1) is rewritten as

$E_{int} = E + E_3$

Calculation of E_3

Let us consider small area ds on the surface of the spherical cavity. It is confined within an angle $d\theta$ at the angle θ in an direction of electric field

Polarization P is parallel to E . P_N is the component of polarization perpendicular to the area ds as shown in the figure.

$$PN = P \cos \theta$$

q' is the area charged. Polarization is so defined as the surface charges per unit area. q' / ds

$$PN = P \cos \theta = (q' / ds)$$

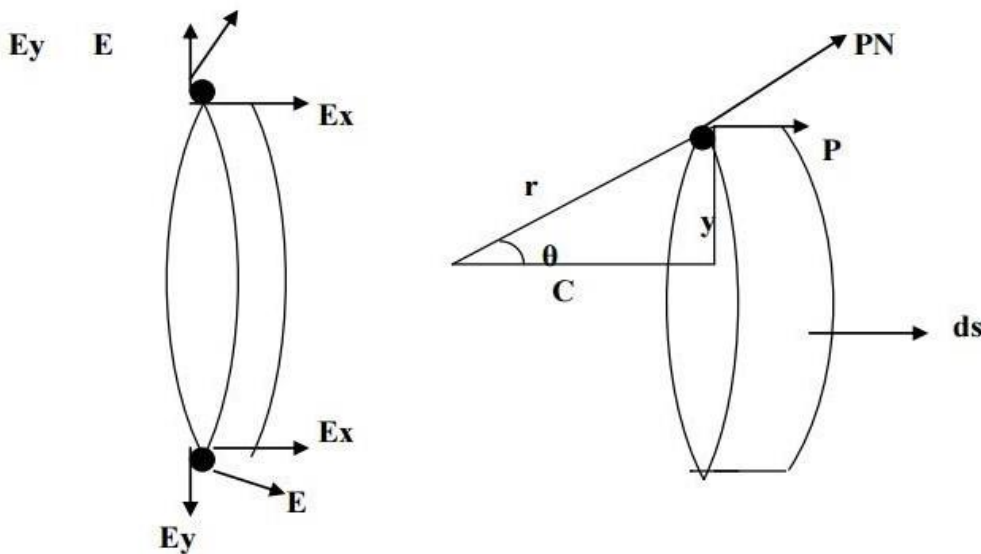
Electric field intensity at C due to charge q' (Coulomb force) is given by

$$E = \frac{q'}{4\pi\epsilon_0 r^2}$$

Substituting for q' from equation 3, we have

$$E = \frac{P \cos \theta ds}{4\pi\epsilon_0 r^2}$$

This electrical field intensity is along the radius r and it can be resolved into two components (E_x and E_y) as shown in figure.



The component of intensity parallel to the electrical field direction,

$$E_x = E \cos \theta$$

Substituting for E from equation 4 in 5, we have

The component of intensity perpendicular to the field direction,

$$E_x = \frac{P \cos \theta \cos \theta ds}{4\pi\epsilon_0 r^2}$$

$$E_x = \frac{P \cos^2 \theta}{4\pi\epsilon_0 r^2}$$

$$E_x = E \sin \theta$$

Since the perpendicular components are in opposite directions, they cancel out each other. Hence, the parallel components alone are taken onto consideration.

Now, consider a ring area dA which is obtained by revolving ds about AB as shown in fig(b)

Substituting equation 7 in 8, we have

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

$$E = \frac{P \cos^2 \theta \sin \theta \, d\theta}{2\epsilon_0}$$

Substituting equation 7 in 8, we have

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

$$E = \frac{P \cos^2 \theta \sin \theta \, d\theta}{2\epsilon_0}$$

$$E_3 = \int_0^\pi \frac{P \cos^2 \theta \sin \theta \, d\theta}{2\epsilon_0}$$

$$E_3 = \frac{P}{2\epsilon_0} \int_0^\pi \cos^2 \theta \sin \theta \, d\theta$$

$$E_3 = \frac{P}{2\epsilon_0} \times 2/3 \left(\int_0^\pi \cos^2 \theta \sin \theta \, d\theta = 2/3 \right)$$

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

Substituting equation 10 in equation 2, we get

$$\mathbf{E}_3 = \mathbf{E} + \frac{\mathbf{P}}{3\epsilon_0}$$

E_{int} is the internal field or Lorentz field.

CLAUSIUS – MOSOTI EQUATION

Let N be the number of molecules per unit volume and α be the molecular polarizability.

Then

Total polarization, $P = N \alpha E_{int}$

$$E_{int} = \frac{P}{N\alpha}$$

Further, we know that $\mathbf{D} = \epsilon\mathbf{E} = \epsilon_0\mathbf{E} + \mathbf{P}$

$$(\epsilon - \epsilon_0) \mathbf{E} = \mathbf{P}$$

$$\mathbf{E} = \frac{\mathbf{P}}{(\epsilon - \epsilon_0)}$$

Lorentz field
$$E_{int} = \mathbf{E} + \frac{\mathbf{P}}{3\epsilon_0}$$

Substituting equation 2 in equation 3 we have

Lorentz field
$$E_{int} = \frac{\mathbf{P}}{(\epsilon - \epsilon_0)} + \frac{\mathbf{P}}{3\epsilon_0}$$

$$= \left(\frac{\mathbf{P} \quad 3\epsilon_0 + (\epsilon - \epsilon_0)}{3\epsilon_0 (\epsilon - \epsilon_0)} \right)$$

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

Equating equations 1 and 4, we have

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

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

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

$$\frac{Na}{3\epsilon_0} = \frac{\epsilon_r - 1}{\epsilon_r + 2\epsilon_0}$$

$$\left(\frac{\epsilon}{\epsilon_0} = \epsilon_r \right)$$

Where ϵ_r is dielectric constant.

Equation 5 is Clausius- Mosotti relation which relates the dielectric constant (a macroscopic quantity) of the material with polarizability (a microscopic quantity).

DIELECTRIC BREAKDOWN

When a dielectric is placed in an electric field and if the electric field is increased, when the field exceeds the critical field, the dielectric loses its insulating property and becomes conducting. i.e., large amount of current flows through it. This phenomenon is called dielectric breakdown.

The electric field strength at which the dielectric breakdown occurs is known as dielectric

The dielectric strength = strength. Dielectric voltage / Thickness of dielectric

TYPES OF DIELECTRIC BREAKDOWN

Intrinsic or avalanche breakdown Thermal breakdown

Chemical and electrochemical breakdown Discharge breakdown

Defect breakdown

INTRINSIC BREAKDOWN

When dielectric is subjected to electric field then the electrons in the valance band acquire sufficient energy and go to conduction band by crossing the energy gap and hence become conduction electrons. Therefore large current flows and it is called intrinsic breakdown or zener breakdown.

AVALANCHE BREAKDOWN

These conduction electrons on further application of field then collide with the valance electrons in the co-valent band and remove more electrons hence transferring them as conduction electrons.

These secondary conduction electrons again dislodge some other bound electrons in the valance band and this process continues as a chain reaction. Therefore very large current flows through the dielectrics and hence called as avalanche breakdown.

Characteristics

It can occur at lower temperatures.

It requires relatively large electric fields.

This kind of breakdown occurs in thin samples. It occurs within short span of time.

THERMAL BREAKDOWN

In general, when a dielectric is subjected to an electric field, heat is generated. This generated heat is dissipated by the dielectric. In some cases the heat generated will be very high compared to the heat dissipated. Under this condition the temperature inside the dielectric increases and heat may produce breakdown. This type of breakdown known as thermal breakdown.

Characteristics

It occurs at higher temperatures.

It requires moderate electric fields.

It depends on the size and shape of the dielectric material. It occurs in the order of milliseconds.

CHEMICAL AND ELECTROCHEMICAL BREAKDOWN

This type of breakdown is almost similar to the thermal breakdown. If the temperature is increased mobility of ions will increase and hence the electrochemical reaction may be induced to take place.

Therefore when mobility of ions increased, insulation decreases and hence dielectrics becomes conducting. This type of breakdown is called as chemical and electrochemical breakdown.

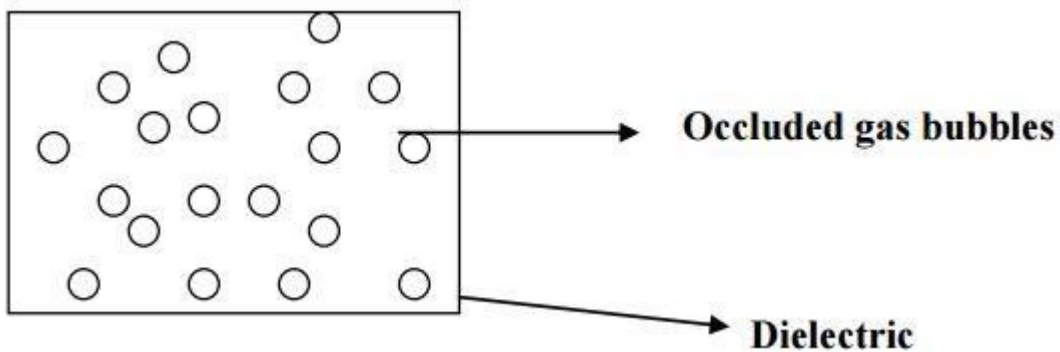
Characteristics

It occurs only at low temperatures.

It depends on concentration of ions, magnitude of leakage current. It occurs even in the absence of electric field.

DISCHARGE BREAKDOWN

Discharge breakdown occurs when a dielectric contains occluded air bubbles as shown in fig. when this type of dielectric subjected to electrical field, the gases present inside the material will easily ionize and thus produce large ionization current. This is known as discharge breakdown.



Characteristics

It occurs at low voltages.

It occurs due to the presence of occluded air bubbles. It depends upon the frequency of the applied voltage.

DEFECT BREAKDOWN

Some dielectric have defects such as cracks, pores, blow holes etc. these vacant position may have moisture which leads to breakdown called as defect breakdown.

REMEDIES FOR BREAKDOWN MECHANISMS

To avoid breakdown, the dielectric material should have the following properties. It should have high resistivity.

It must possess high dielectric strength.

It should have sufficient mechanical strength. Dielectric loss should be low.

Thermal expansion should small. It should be fire proof.

It should resistive to oils, liquids and gases. It must have less density.

There should not be any defects. It must be in pure form.