DIELECTRIC PROPERTIES

Dielectrics are the materials having electric dipole moment permanently or temporarily by applying electric field. These are mainly used to store electrical energy and as electrical insulators. There are no free electrons available for conduction in a dielectric. All electrons are tightly bound to their respective nucleus of atoms. All dielectrics are electrical insulators. But all electrical insulators need not be dielectrics. For example the vacuum is a perfect insulator. But it is not a dielectric. The study of dielectrics is essentially study of insulators. Dielectrics are characterized by Polarization and dielectric constant. These characteristics are strongly frequency-dependent.

BASIC DEFINITIONS:

Electric Dipole: -q------------r------------+q

Two opposite charges of equal magnitude separated by a finite distance constitutes an electric dipole.

Consider two opposite charges of equal magnitude +q and –q separated by a distance r as shown in fig. These two charges constitute an electric dipole

Dipole Moment

Dipole moment is the equal to the product of one of the charges and the charge separating distance. The dipole moment is given by

It is a vector quantity pointing from a negative charge towards positive charge. Its unit is Coulomb-meter (C-m) or debye

$$1 \text{debye} = 3.3 \times 10^{-30} \text{ C-m}$$

Permittivity (ε)

Permittivity represents the easily polarisable nature of the dielectric material or medium. The permittivity of a dielectric is denoted by and the permittivity of free space or air is denoted by ε_0. The value of $\varepsilon_0 = 8.854 \times 10^{-12} \text{ Fm}^{-1}$.

Dielectric constant (ε_r) or Relative permittivity of the medium

The ratio between the capacity with dielectric to the capacity without dielectric is known as dielectric constant (ε_r)

$$\varepsilon_r = \frac{C_d}{C_0} \text{ (or) } \varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \Rightarrow \varepsilon = \varepsilon_r \varepsilon_0$$

As shown in the fig consider a capacitor with air as a medium having a charge Q as its plates separated by a distance d. Let A be the Area of the cross section of the plate, V_0 is the potential difference and E_0 be the electric field across the plates. Now the capacity of the capacitor is given by
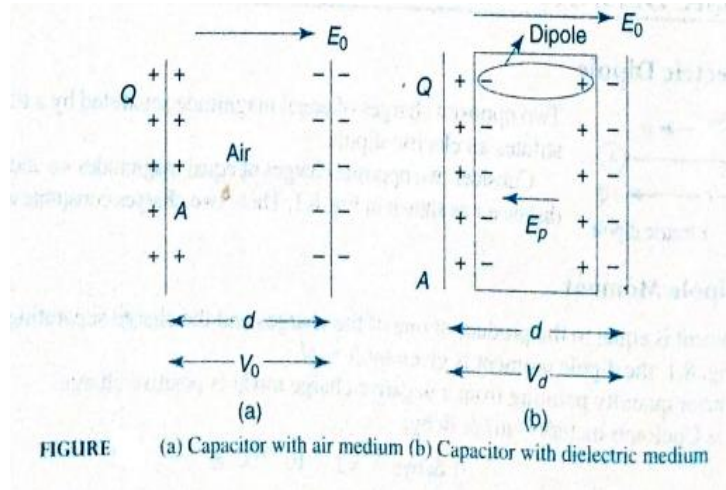

FIGURE   (a) Capacitor with air medium (b) Capacitor with dielectric medium

$$C = \frac{Q}{V_0} = \frac{A\varepsilon_0}{d}$$ --- (1)

Where ε_0 is the permittivity of free space or air.

When the dielectrics is introduced into the capacitor, opposite charges are induced into the two faces of dielectric, which are close to the charged plates. These induced positive and negative charges act as dipoles and it has net dipole moment. This phenomenon is known as dielectric polarisation. Due to the dipoles, the resultant potential difference decreases so that storage of charge can be increased. As a result, the capacity increases. Due to polarisation, an electric field known as polarisation electric field E_P is induced in the opposite direction to E_0. Let V_d be the resultant potential difference across the plates. Then the capacity is given by

$$C = \frac{Q}{V} = \frac{A\varepsilon}{d}$$ -------------------------------------- (2)

From 1&2 equations

$$\varepsilon_r = \frac{C_d}{C_0}$$

The above equation is known as dielectric constant (ε_r)

Dielectric polarization (P)

When a dielectric substance is placed in an electric field, then positive and negative charges are displaced in opposite direction.

 The displacement of charges produces local dipoles.

  This process of producing dipoles by the influence of electric field is called electric polarization.

Dielectric Polarization $P = \dfrac{dipole \cdot moment}{volume} = \dfrac{\mu}{V}$

$P = \dfrac{\mu \times l}{A \times l} = \dfrac{q}{A}$, $P = \dfrac{Ch\,\arg e}{Area}$ surface charge density 'σ'

The unit polarisation is C m-2. It is a vector quantity and the pointing from negative charge to positive charge. If μ is the average dipole moment per molecule and N is the number of molecules per unit volume then

$$\textbf{P=N}\mu$$

Dielectric Polarisability (α)

The ability of a dielectric to allow its charges to get separated in the presence of an electric field is known as polarisability. The net dipole moment μ is proportional to the applied electric field 'E'

$$\mu \propto E$$

$$\mu = \alpha\ E$$

Where proportional α is known as the dielectric polarisability.

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

When E=1 and P=μ

Dielectric polarisability is the net dipole moment induced per unit applied electric field. The unit of polarisability is Fm^2.

The above equation we get   P =N α E

Dielectric Susceptibility (χ):

It measures the amount of polarization in a given electric field produced in a dielectric. Polarization is proportional to the product of ε_0 and applied electric field.

$$P \propto \varepsilon_0 E$$

$$P = \chi \, \varepsilon_0 E$$

χ **Is the proportionality constant is known as dielectric Susceptibility.**

$$\chi = \frac{P}{\varepsilon_0 E} \qquad \text{It has no units}$$

Displacement vector or Electric flux density ($\overline{D}$ or D):

Consider a polarised dielectric in a resultant electric field E. the field is characterised by electric lines of forces. These lines of forces pass through the dielectric make it polarised.

The total no of electric lines of force passing through the dielectric is known as electric flux density 'D'.

$$D = \varepsilon_0 E + P$$

But $\quad D = \varepsilon E$

$$\varepsilon E = \varepsilon_0 E + P$$

$$[\because \varepsilon = \varepsilon_0 \varepsilon_r]$$

$$\varepsilon_0 \varepsilon_r E = \varepsilon_0 E + P$$

$$\varepsilon_0 E(\varepsilon_r - 1) = P$$

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

$$\varepsilon_r - 1 = \chi \left[\because \chi = \frac{P}{\varepsilon_0 E} \right]$$

FIGURE Electric lines of forces in a polarised dielectric
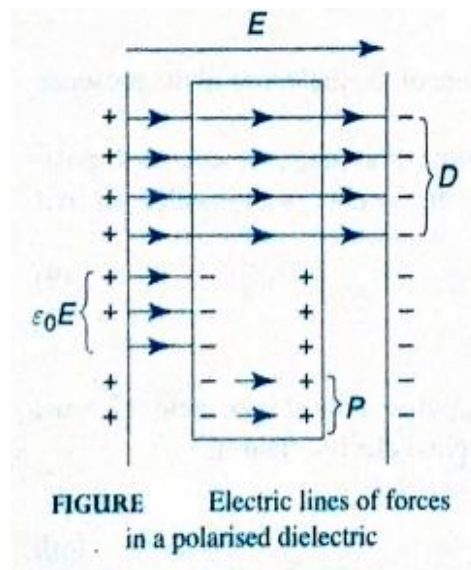
Types of Polarizations

Depending upon the type of displaced charges causing polarization of dielectric in the presence of an electric field. We have three types of polarizations.

1. Electronic Polarization (α_e)

2. Ionic Polarization (α_i)

3. Orientation Polarization (α_O)

Electronic polarization (α_e):

The electronic polarization takes place in all dielectrics due to displacement of charge centers of electron cloud and the nucleus of an atom in the presence of an external electric field.

Let us consider an atom of dielectric material of radius 'R' and nuclear charge $+q = +Ze$, where Z is the atomic number. The electronic charge, $-q = -Ze$ distributed uniformly throughout a sphere of radius R, and it is known as electron cloud.

Case-I: Zero electric field (E = 0)

In the absence of external electric field, i.e., $E = 0$, the center of electron cloud coincides with that of the positive nucleus as shown in Figure. Hence, no dipolemoment exists. The negative charge density of atom of radius R is given as

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

Case-II: Non-zero electric field (E ≠ 0)

When the dielectric is placed in an external electric field of strength E, then two phenomenon happens.

(1) The positively charged nucleus and the negatively charged electron cloud experiences a Lorentz force (F_L) in opposite directions. As a result, the nucleus moves in the direction of applied electric field and the electron cloud undergoes a net displacement, x in a direction opposite to the applied electric field as shown in figure.

$$F_L = Ze.E$$
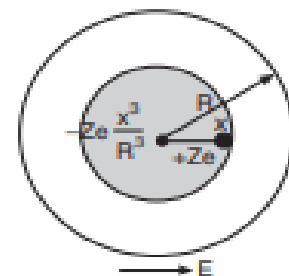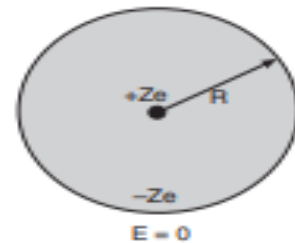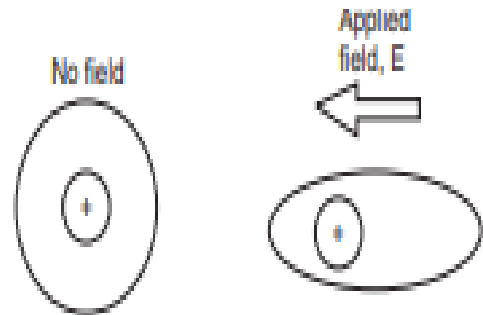
(2) When the nucleus and electron cloud are displaced from their equilibrium positions, a Coulomb attractive force (F_C) come into play to maintain them into their original positions.

$$F_C = \frac{1}{4\pi\varepsilon_0} \cdot \frac{-q \times q}{x^2}$$

The total negative charge in the sphere of radius, x is given as

$-q =$ **Volume of the sphere . Charge density**

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

$$\Rightarrow q = -Ze\left(\frac{x}{R}\right)^3$$

Total positive charge enclosed in a sphere of radius, x is given as

$$+q = +Ze$$

It is known that the Lorentz force will tend to separate them from their equilibrium positions. At equilibrium,

Lorentz force = –Coulomb force

$$F_L = -F_C$$

$$\Rightarrow Ze.E = \frac{-1}{4\pi\varepsilon_0} \cdot (-Ze)^2 \frac{x}{R^3}$$

$$\therefore x = 4\pi\varepsilon_0 \cdot \frac{R^3}{Ze} .E$$

When the electric field is applied, the charge centers are displaced from their equilibrium positions and the atom gains some dipolemoment, called the induced dipolemoment (μ) and it is given as

$$\mu = Ze \cdot x$$

$$\mu = Ze \times 4\pi\varepsilon_0 \cdot \frac{R^3}{Ze} .E$$

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

We know that the dipolemoment (μ) is directly proportional to the applied electric field strength (E).

$\mu \propto E$ $\Rightarrow \mu = \alpha_e.E$

Where α_e is known as electronic polarizability.

$$\alpha_e = 4\pi\varepsilon_0.R^3$$

Conclusions:

(i) The electronic polarization sets in over a very short period of time, of the order of 10^{-14} to 10^{-15}s.

(ii) Electronic polarizability depends on the volume of the atom only.

(iii) Electronic polarizability is in dependent of temperature.

Ionic polarization (α_i):

The ionic polarization occurs in ionic dielectrics only. It is mainly due to the displacement of cations and anions in opposite direction in the presence of applied electric field. Let us consider a cation (positive ion) and an anion (negative ion) of mass M and m, respectively.

Case-I: Zero electric field (E = 0)

In the absence of external electric field, i.e., E = 0, the spheres of influence of both cation and anion are in contact as shown in figure-1. Let x_0 is the equilibrium distance between the two charge centers. As the displacement between the cation and anion is zero, no dipolemoment exists.

Case-II: Non-zero electric field (E ≠ 0)

When an external electric field E is applied on ionic dielectric, then positive ions get displaced in the direction of applied field and the negative ions displaced in opposite to the applied field from their equilibrium positions due to the Lorentz force existed as shown in figure-2. Let X_1 and X_2 be the displacements of positive and negative ions, respectively.

(1) Electric field, $\overline{E} = 0$

(2) Electric field, $\overline{E} \neq 0$
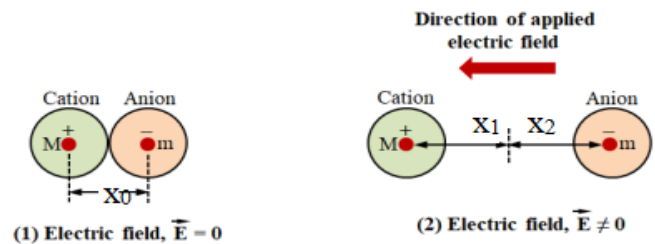
The total displacement between the two charge centers is given as

$$X = X_1 + X_2 \text{------------------------- (1)}$$

The Lorentz force on positive ion, $F_L = +eE$

Similarly, the Lorentz force on negative ion, $F_L = -eE$

When ions are displaced from their equilibrium position, then restoring force developed between the ions and it tend to bring them into their original positions.

The restoring force acting on positive ion, $F_R = K_1.X_1$

Similarly, the Lorentz force on negative ion, $F_R = K_2.X_2$

Where K_1 and K_2 are known as spring constants and they depends on mass of corresponding ions and the angular velocity (ω) of the molecule in which the ions are present.

Therefore, $K_1 = M.\omega^2$ and $K_2 = m.\omega^2$

At equilibrium, Lorentz force = Restoring force

$$\Rightarrow F_L = F_R$$

For Positive Ion, $eE = K_1.X_1$ $\qquad\qquad \Rightarrow X_1 = \dfrac{e.E}{K_1} = \dfrac{e.E}{M\omega^2}$

For Positive Ion, $eE = K_2.X_2$ $\qquad\qquad \Rightarrow X_2 = \dfrac{e.E}{K_2} = \dfrac{e.E}{m\omega^2}$

Substituting X₁ and X₂ values in Eq.1, we obtain

$$X = \frac{e.E}{M\omega^2} + \frac{e.E}{m\omega^2}$$

$$\Rightarrow X = \frac{e.E}{\omega^2}\left(\frac{1}{M} + \frac{1}{m}\right)$$

The dipolemoment (μ) and it is given as

$$\mu = e.x$$

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

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

We know that the dipolemoment (μ) is directly proportional to the applied electric field strength (E).

$\mu \propto E$ $\qquad\qquad\qquad \Rightarrow \mu = \alpha_i E$

where α_i is known as ionic polarizability.

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

(i) Ionic polarizability depends on the masses of ions (cation and anion) only.

 (ii) It is inversely proportional to the square of the natural frequency of the molecule.

(iii) Ionic polarization takes 10^{-11} to 10^{-14} s to build up, and is not influenced by temperature.

(iv) For most materials, the ionic polarizability is less than the electronic polarizability.

$$\text{i.e. } \alpha_i = \frac{1}{10}\alpha_e$$

Orientational polarization (α_o):

The polarization due to the orientation of molecular dipoles in the presence of an applied electric field is known as orientation polarization or dipolar polarization (α_o).

Case-I: Zero electric field (E = 0)

In the absence of external electric field, i.e., E = 0, the dipoles align randomly as shown in figure-1. As a result, no dipolemoment exists.
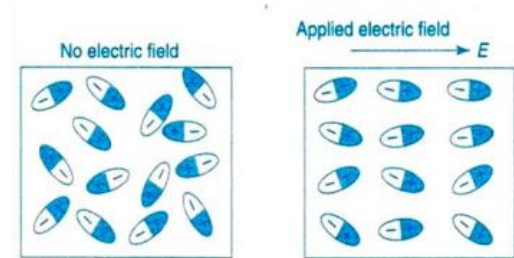
Case-II: Non-zero electric field (E $\neq$ 0)

When an external electric field, E is applied on a polar dielectric material, then all the dipoles tend to align in the direction of applied field as shown in figure-2. Hence, the dipolemoment (μ) increases enormously. The orientation polarization vector (Po) can be written as

Fig. 1   Orientational polarization
Fig. 2

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

Where N is the number of atoms per unit volume, μ is the dipolemoment, E is the applied electric field strength, K is the Boltzmann constant and T is absolute temperature of the material.

In terms of polarizability, the orientation polarization vector (P_o) can be written as

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

Where α_0 is known as orientation polarizability.

Comparing Eq.1 and 2, we obtain

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

$$\Rightarrow \alpha_0 = \frac{\mu^2}{3K.T}$$

Orientational polarizability is inversely proportional to the absolute temperature of the material.

Lorentz internal field:

Definition:

In dielectric solids, the atoms or molecules experienced not only the external applied electric field but also the electric field produced by the dipoles. Thus the resultant electric field acting on the atoms or molecules of dielectric substance is called the "Local field or an internal field."

Imagine a small spherical cavity of radius 'r'. In this sphere inside dipoles are present. Consider a dipole at the center of spherical cavity. This dipole experiences

$E_{Local} = E_I = E_1 + E_2 + E_3 + E_4$ --------------------- (1)
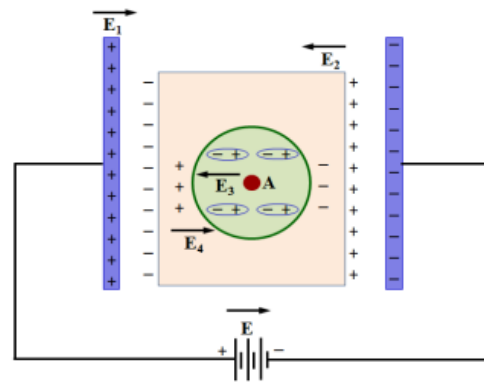
Where E_1 = External applied field.

(a) The field 'E_2' produced by induced charges on the dielectric sample near the surface.

(b) The field E_3 arising from dipoles inside the sphere. E_3 depends on crystal symmetry. [For isotropic materials $E_3 = 0$]

(c) The field E_4 is due to polarization of charges on the surface of spherical cavity. It is called the Lorentz cavity field.

From the above field 'E' be the resultant field due to E_1 and E_2. For a cubic structure, due to symmetrical distribution of charges with in the spherical region $E_3 = 0$. i.e.,

$$\therefore E_{int} = E + E4 \qquad \text{---------------- (2)} \qquad (E = E_1 + E_2 \ \& \ E_3 = 0)$$

Calculation of Field E₄

The enlarged view of the spherical region is shown in figure.

If dA is the surface area of the sphere of radius r lying between θ and $\theta + d\theta$, where θ is the direction with the reference to the direction of the applied field, then

Enlarged view of spherical cavity

$$dA = 2\pi(PQ)(QR)$$

$$Sin\,\theta = \frac{SQ}{r} \Rightarrow SQ = rSin\,\theta,$$

$$d\theta = \frac{QR}{r} \Rightarrow QR = rd\theta \qquad \text{(for Small angle } Sin\,\theta = d\theta\text{)}$$

Hence, $dA = 2\pi rSin\,\theta.rd\theta = 2\pi.r^2Sin\,\theta d\theta$

A surface electric charge should be placed on the spherical surface. At each point of the sphere, the surface charge density is given by

$$\sigma = PCos\theta$$

Where θ is the angle between radius vector r and the direction of E₄. The charge on element dA of the surface of the sphere will be

$$dq = \sigma.dA = PCos\theta.dA$$

This charge will produce electric field intensity dE₄ at the center of the sphere.

$$dE_4 = \frac{dq}{4\pi\varepsilon_0 r^2} = \frac{P}{4\pi\varepsilon_0 r^2}\cos\theta.dA$$

This electric field can be resolved into two components: one component $dE_4Cos\theta$ parallel to the direction of E and the other $dE_4Sin\theta$ perpendicular to the direction of E.

$$dE_4Cos\theta = \frac{P}{4\pi\varepsilon_0 r^2}\cos^2\theta.dA$$

$$dE_4Sin\theta = \frac{P}{4\pi\varepsilon_0 r^2}\cos\theta.Sin\theta.dA$$

It is obvious that the perpendicular components of the upper and lower half of the sphere cancel each other and only the parallel components contribute to the total intensity E₄.

$$E_4 = \int_0^\pi dE_4 \, Sin\,\theta = \int_0^\pi \frac{P}{4\pi\varepsilon_0 r^2}.Cos^2\theta.dA \qquad (\text{Hence,}\, dA = 2\pi r Sin\,\theta.rd\theta = 2\pi.r^2 Sin\,\theta d\theta\,)$$

$$E_4 = \int_0^\pi dE_4 \, Sin\,\theta = \int_0^\pi \frac{P}{4\pi\varepsilon_0 r^2}.Cos^2\theta.2\pi.r^2 Sin\,\theta d\theta$$

$$E_4 = \frac{P}{2\varepsilon_0}\int_0^\pi .Cos^2\theta.Sin\,\theta d\theta$$

Let $Cos\theta = x$ and therefore, $-Sin\,\theta d\theta = dx$

$$E_4 = \frac{P}{2\varepsilon_0}\int_1^{-1} x^2 dx = -\frac{P}{2\varepsilon_0}\left[\frac{x^3}{3}\right]_{+1}^{-1}$$

$$E_4 = -\frac{P}{6\varepsilon_0}\left[-1-1\right] = \frac{2P}{6\varepsilon_0} = \frac{P}{3\varepsilon_0}$$

From the equation (2) $\qquad E_{int} = E + E_4$

$$E_{int} = E + \frac{P}{3\varepsilon_0} \text{ or } E_{int} = E + \frac{\gamma P}{\varepsilon_0} \text{ where } \Upsilon = 1/3 \text{ is called the internal filed}$$

constant.

This equation is known as Lorentz internal field.

NOTE: Lorentz internal field is greater than the applied electric field

Clausius-Mossotti equation:

The relation between the dielectric constant and polarisability of a polarised dielectric is known as Clausius-Mossotti equation (or) relation. To derive the relation,

Let us consider a polarised dielectric in which E_i is the local field. Then induced dipole moment is proportional to E_i. $\qquad \mu \propto E_i$

$$\mu = \alpha E_i$$

Where α is the polarisability of dielectric. If N is the number of atoms per unit volume of a dielectric, then polarisation is given by

$$P = N\mu$$

P= NαE_i

$$P = N\alpha \left[E + \frac{P}{3\varepsilon_0} \right] \Rightarrow P = N\alpha E + \frac{N\alpha P}{3\varepsilon_0}$$

$$N\alpha E = P\left(1 - \frac{N\alpha}{3\varepsilon_0} \right)$$

$$P = \frac{N\alpha E}{\left(1 - \dfrac{N\alpha}{3\varepsilon_0} \right)} \quad \text{-----------------------} \quad (1)$$

$$P = \varepsilon_0 E(\varepsilon_r - 1) \text{--------------------} (2)$$

From Eq (1) and (2)

$$\varepsilon_0 E(\varepsilon_r - 1) = \frac{N\alpha E}{\left(1 - \dfrac{N\alpha}{3\varepsilon_0} \right)}$$

$$\left(1 - \frac{N\alpha}{3\varepsilon_0} \right) = \frac{N\alpha E}{\varepsilon_0 E(\varepsilon_r - 1)}$$

$$1 = \frac{N\alpha E}{\varepsilon_0 E(\varepsilon_r - 1)} + \frac{N\alpha}{3\varepsilon_0}$$

$$1 = \frac{N\alpha}{3\varepsilon_0} \left(\frac{3}{\varepsilon_r - 1} + 1 \right)$$

$$\frac{N\alpha}{3\varepsilon_0} = \frac{1}{\left(\dfrac{3}{\varepsilon_r - 1} + 1 \right)}$$

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

This equation is known as Clausius-Mossotti equation.

Significance of Clausius-Mossotti equation:

1) The Clausius-Mossotti equation is used to determine the polarizabilities of atoms if the dielectric constant is known.

2) It is used to predict the dielectric constants of new materials knowing their polarizabilities.

3) It is used to know the relation between the dielectric constant and polarizability of a dielectric material.

Complex dielectric constant:

Statement: A complex-valued quantity that characterizes the response of a material to an applied electric field is called the complex dielectric constant. It is also called as complex permittivity.

The complex dielectric constant is used to describe the dielectric constant during a periodic variation of the electric field. It is defined as:

$$\varepsilon^* = \varepsilon'(\omega) + \varepsilon''(\omega) \qquad (1)$$

Where the subscript 'ω' indicates that the dielectric constant can depend on the frequency of the applied electric field.

$\varepsilon'(\omega)$ is the real part of the dielectric constant and it is related to the ability of a material to store electric charge when an electric field is applied.

$\varepsilon''(\omega)$ is the imaginary part of the dielectric constant and it is the dielectric loss factor.

The ratio of imaginary to real dielectric constant is the loss tangent of the dielectric material.

$$\tan \delta = \frac{\varepsilon''(\omega)}{\varepsilon'(\omega)} \qquad (2)$$

Uses of complex dielectric constant:

The complex dielectric constant is a used

1. To study the behavior of materials in electric fields.

2. To study the propagation of electromagnetic waves through materials

3. in the design of electronic devices.

Physical significance of complex dielectric constant:

• The complex dielectric constant is a fundamental parameter.

• It characterizes the response of a material to an applied electric field.

• It can be measured experimentally using the techniques such as dielectric spectroscopy or impedance spectroscopy.

• It has both real and imaginary parts which depend on the frequency of the field variation.

Dielectric Loss:

Statement: The dissipation of electrical energy inside a dielectric when subjected to electric fields (A.C. or D.C.) is known as dielectric loss.

Usually, it is expressed in terms of power loss, which is defined as the average electrical power dissipated in a dielectric during certain interval of time.

When an A.C. voltage is applied to a perfect dielectric such as vacuum or purified gas as shown in Fig.(a), it does not absorb electrical energy and there is no loss of electrical energy. Thus, polarization of the dielectric is in phase with voltage. In such a case, the charging current leads the applied voltage by an angle 90° as shown in Fig. (b).

Fig.(a)   Fig.(b)   Fig.(c)
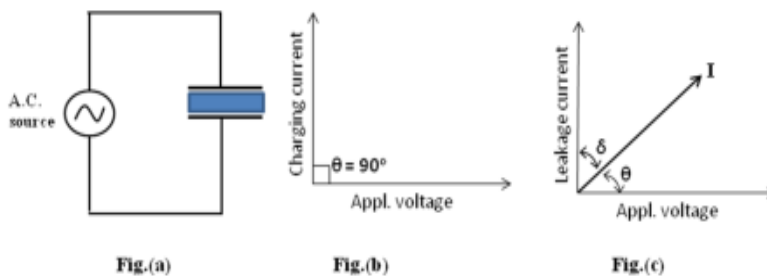
The power loss in dielectric can be written as

PL = V.I. cosθ --- (1)

For perfect dielectric, θ =90° ⟹ PL = 0

Practically, a dielectric always has some loss of electrical energy. Hence, the leakage current leads the applied voltage by an angle (90° -δ) as shown in Fig. (c), resulting some loss in electrical energy. Here, δ is known as dielectric loss angle and it is a measure of electrical power dissipated in each cycle. Now Eq. (1) can be written as

PL = V.I. cos (90o -δ) = V.I. sinδ ----------------------------------- (2)

The frequency of applied voltage, $f = \dfrac{1}{2\pi X_c C}$

where $X_c = \dfrac{V}{I}$ called the capacitive reactance. Therefore, $I = V.2\pi.f.C$

Now Eq.2 can be written as $P_L = V.2\pi.f.CV.\sin \delta$

Since, δ is very small, then sinδ ≅ tanδ

$$\therefore P_L = 2\pi.f.c.V^2 \tan \delta \text{---} (3)$$

Where tan δ is called the dissipative factor or Loss tangent.

From Eq.(3) it is clear that the power loss varies with the frequency of applied voltage and it is shown in following figure.
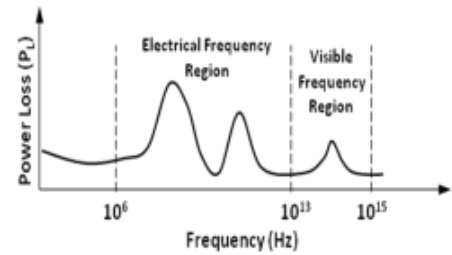
This figure clears that the power loss is relatively small in optical frequency region compared to that of electrical frequency region

Difference between the simple and complex dielectric constants:

Simple Dielectric constant (ε)	Complex dielectric constant (ε*)
• It is a fundamental parameter of a dielectric.	• It is an important parameter of a dielectric.
• It is a real number that represents the ratio of the electric flux density in a vacuum to the electric flux density in the material.	• It is a complex number that has both real and imaginary parts.
• $\varepsilon_r = \varepsilon_{medium} / \varepsilon_{vacuum}$	• $\varepsilon^*(\omega) = \varepsilon'(\omega) + \varepsilon''(\omega)$
• It is also known as the static or real dielectric constant.	• The real part ε'(ω) belongs to energy storage, while the imaginary part ε''(ω) belongs to energy dissipation.
• It is a measure of a material's ability to store electric charge when an electric field is applied.	• It is a measure of the response of a material to an oscillating electric field at a given frequency.
• It does not vary with frequency of applied field.	• It varies with frequency of applied field.
• It is used in the design of electronic devices, such as capacitors and insulators.	• It is used in the design and analysis of high-frequency electronic devices, such as antennas and microwave circuits.

Application of dielectrics:
• Some of the most significant applications of the dielectrics are:
1. Dielectrics are used as capacitor materials to store electrical energy.
2. They are used as an insulator in a transformer.
3. They are used as a cooling agent in transformers.
4. They can be used to enhance the performance of semiconductor devices.
5. They can be used in sensor devices.
6. They can be used to increase the speed of signal transmission.
7. They can be used in microwave devices.
8. They can be used to remove moisture content in oil emulsions.
9. They are used in the design of antennas communication.
10. They can be used in liquid crystal display

3.2. Magnetic Materials

The phenomenon by which materials bring attractive or repulsive forces on other materials is known as "magnetism". All materials do not show magnetism but certain materials possess different types of magnetism. The underlying factor responsible for the creation of a magnetic field is the presence of charge. Although magnetic charge does not exist in nature, the movement of charge generates a magnetic field. Therefore, the magnetic characteristics of solids stem from the motion of electrons. . Thus, they are known as diamagnetic, paramagnetic, ferromagnetic, antiferromagnetic and ferrimagnetic materials. Ferromagnetic materials are further classified into soft and hard materials. These materials are widely used in information storage devices

Basic Definition:

Magnetism: The attracting property exhibited by the magnet is known as magnetism

Magnetic dipole: A magnet consists of north and south poles. Any two opposite poles are separated by a finite distance constitute a magnetic dipole.

Magnetic dipole moment or magnetic moment If 'm' is the magnetic pole strength and '2l' is the length of the magnet then its magnetic dipole moment or magnetic moment is given by the products m × 2l. It is denoted by mm.

When an electric current of I ampere flows through a circular wire of one turn having an area of cross section Am^2, it is said to have a magnetic moment of

$$\mu_m = IA$$

It is expressed in Am^2. It is a vector quantity pointing from South to North Pole.

Magnetic field: The space surrounding the magnet up to which its attracting property influence is felt is known as magnetic field.

Magnetic field strength (H):

The magnetic field intensity at any point in a magnetic field is the force experienced by a unit North Pole placed at a point.

Mathematically, $$H = \frac{B}{\mu_0} - M$$

Where B is the magnetic flux density, M is the intensity of magnetization and μ_0 is the magnetic permeability of free space. It is expressed in the units of ampere per meter $(A\text{-}m^{-1})$.

Magnetisation or intensity of magnetisation (M):

When a material is magnetized, it develops a net magnetic moment. The magnetic moment per unit volume is called intensity of magnetization (M).

$$M = N.\bar{\mu}_m$$

Where N is the number of atoms per unit volume and $\bar{\mu}_m$ is the average magnetic moment.

It is expressed in the units of ampere per meter (A-m $^{-1}$) .

Magnetic susceptibility (χ)

The magnetic susceptibility χ is defined as the ratio of the magnetisation produced in a sample to the magnetic field strength.

$$\chi = \frac{M}{H}$$

It has no units

Magnetic lines of forces: The magnetic field is characterised by magnetic lines of forces.

Magnetic induction field strength (or) Magnetic flux density (B)

The magnetic flux density B is defined as the number of magnetic lines of force passing through a unit area of cross section of magnetic material.

If ϕ is the number of magnetic lines of forces that passes through 'A' area of cross section of a material, then

$$B = \frac{\phi}{A}$$ It expressed in Wb-m^{-2} or Tesla

Magnetic permeability (μ): The magnetic permeability m is a measure of the amount of magnetic lines of forces penetrating through a material. It is defined as the ratio of the magnetic flux density (or) magnetic induction field strength B in the material to the applied magnetic field intensity H. That is,

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

$$\Rightarrow B = \mu H$$

Magnetic permeability of free space (μ_0): The magnetic permeability of free space μ_0 a measure of the amount of magnetic lines of forces passing through the air medium. It is defined as the ratio of magnetic induction field strength B$_0$ of a free space or air to the applied magnetic field strength H.

$$\mu_0 = \frac{B_0}{H} \Rightarrow B_0 = \mu_0 H \text{ Where } \mu_0 = 4\pi \times 10^{-7} \, Hm^{-1}$$

Relative magnetic permeability (μ_r)

It is defined as the ratio of permeability of a material to the permeability of free space.

$$\mu_r = \frac{\mu}{\mu_0} \Rightarrow \mu = \mu_r \mu_0$$

Relation between B, M and H

Relation between B, H and M

$$B = \mu H$$
$$= \mu_0 \mu_r H$$
$$B = \mu_0 \mu_r H + \mu_0 H - \mu_0 H$$

But
$$M = H(\mu_r - 1)$$
$$B = m_0 H + \mu_0 M$$
$$B = \mu_0 (H + M)$$

Relation between χ and μ_r

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

$$\mu_0 = \frac{B}{H + M}$$

$$\mu_r = \frac{\mu}{\mu_0} = \frac{B/H}{B/H + M} = \frac{H + M}{H} = 1 + \frac{M}{H}$$

$$\mu_r = 1 + \chi \quad \left(\because \chi = \frac{M}{H} \right)$$

ORIGIN OF MAGNETIC MOMENT–BOHR MAGNETON

Materials are made up of atoms. These atoms consist of a nucleus surrounding which electrons are revolving in their orbits.

The orbital motion of electrons establishes a magnetic moment, called the orbital magnetic moment of electrons. While revolving round the nucleus, the electrons spin about their own axes and cause a magnetic moment, called the spin magnetic moment of electrons. The nucleons in the nucleus also spin and results a magnetic moment, known as spin magnetic moment of nucleus.

The orbital and spin motion of electrons and the spin motion of nucleus are illustrated in the figure. Therefore, the permanent magnetic moment of magnetic materials originate due to the following.
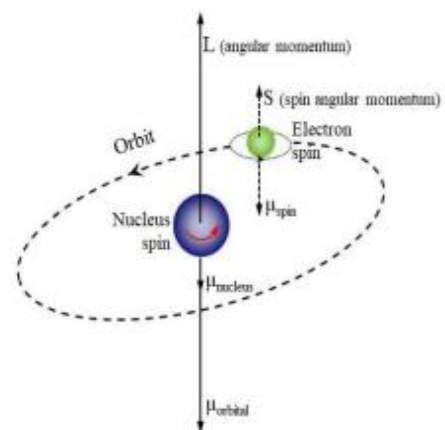
(i) The orbital magnetic moment of electrons ($\mu_{orbital}$)

(ii) The spin magnetic moment of electrons (μ_{spin})

(iii)The spin magnetic moment of nucleus ($\mu_{nucleus}$)

Orbital magnetic moment of electron ($\mu_{orbital}$):

Consider an electron of mass 'm', charge 'e' revolving around the nucleus in a circular orbit of radius 'r' in anticlockwise direction. Let 'v' be the linear velocity of electron and 'w' the angular velocity (angular frequency) of a revolving electron.

Then the linear frequency of the revolving electron $= \dfrac{\omega}{2\pi}$

Time period of revolutions $= \dfrac{2\pi}{\omega}$

The revolving electron in circular orbit establishes a current given by orbital

$$I = \frac{ch\arg e}{time.period} = e\frac{\omega}{2\pi}$$

The current 'I' establishes a magnetic field around the circular orbit. So the upper surface acts as South Pole and the lower surface acts as North Pole. The area of the orbit is $A = \pi r^2$.

Then the corresponding magnetic moment is given by

$$\mu_{orbital} = IA = e\frac{\omega}{2\pi}\pi r^2$$

$$\mu_{orbital} = \frac{e\omega r^2}{2}$$

This orbital magnetic moment is pointing from S-pole to N-pole, i.e., in the downward direction.

The angular momentum of the revolving electron is given by Angular momentum = Linear momentum × Radius
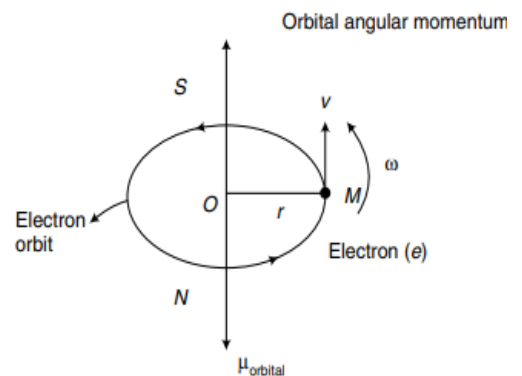
Figure   Revolving electron in an atom

$$= mvr$$

$$= m\omega r^2 \quad (v = \omega r)$$

$$\therefore \mu_{orbital} = \frac{e\omega r^2}{2}$$

$$\Rightarrow \therefore \mu_{orbital} = \frac{e}{2m} \times m\omega r^2$$

$$\Rightarrow \therefore \mu_{orbital} = -\left[\frac{e}{2m}\right] \times (orbital \cdot angular \cdot momentum)$$

The –ve sign indicates that the orbital angular momentum and magnetic moment are in opposite directions.

Then the orbital gyromagnetic ratio $= \gamma = \dfrac{Magnetic \cdot moment}{orbital \cdot angular \cdot momentum} = \gamma = \dfrac{e}{2m}$

According to modern atomic theory, the angular momentum of an electron in the orbit is determined by the orbital quantum number 'l'. Angular momentum of electrons associated with **orbital quantum number 'l' is given by** $l\left(\dfrac{h}{2\pi}\right)$

$$\therefore \mu_{orbital} = -\left[\frac{e}{2m}\right] \times (orbital \cdot angular \cdot momentum)$$

$$= -\left[\frac{e}{2m}\right] \times \left(\frac{lh}{2\pi}\right)$$

$$\therefore \mu_{orbital} = -\left[\frac{eh}{4\pi m}\right] l$$

$$\therefore \mu_{orbital} = -\mu_B \cdot l \quad \text{where } l = 1,2,3,4\text{-----}$$

$$\therefore \mu_{orbital} = -\mu_B, -2\mu_B, -3\mu_B, -4\mu_B \ldots\ldots$$

Where $\mu_B = \left(\dfrac{eh}{4\pi m}\right)$ is a fundamental unit of magnetic moment known as Bohr magneton, and its value is **9.28 × 10⁻²⁴ Am².**

Charge of electron, $q = -1.6\times10^{-19}$ C

Mass of electron, $m = 9.1\times10^{-31}$ kg

Planck's constant, $h = 6.63\times10^{-34}$ J s

For the first orbit, $n = 1 \Rightarrow \mu_{orbital} = \mu_B = \dfrac{-1.6\times10^{-19}\,C\times6.63\times10^{-34}\,Js}{4\pi\times9.1\times10^{-31}\,kg}$

$\therefore \mu_{orbital} = \mu_B = -9.28\times10^{-24}\,Am^2$

The spin magnetic moment of electrons (μspin)

The spinning electron about its own axis establishes the magnetic field and we get a magnetic moment known as spin magnetic moment which is given by $\mu_{Spin} = \gamma\left(\dfrac{e}{2m}\right)S$ where γ is the spin gyromagnetic ratio and 'S' is the spin angular momentum.
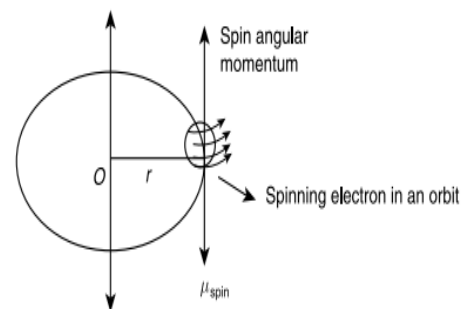

Figure   Spinning electron in an atom

For an electron, $S = \dfrac{h}{4\pi}$, $\therefore \mu_{Spin} = \gamma \left(\dfrac{e}{2m} \right) \left(\dfrac{h}{4\pi} \right)$

Experimental results show that $\gamma \cong -2.0024$. Substituting the known values, we obtain

$$\mu_{spin} = -9.4 \times 10^{-24} \, Am^2$$

Therefore, the magnetic moments due to the spin and orbital motions of electron are of the same order of magnitude.

The spin magnetic moment of nucleus ($\mu_{nucleus}$)

In addition to electronic contribution, nuclear spin also contributes to magnetic moment of atoms. The nuclear spin magnetic moment is given by

$$\mu_{Nuclear \cdot Spin} = \gamma_n \left(\dfrac{eh}{4\pi M_P} \right)$$
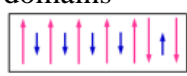
where γ_n represents the spin gyromagnetic ratio of protons and its magnitude is almost unity and M_p represents the mass of proton ($1.67 \times 10{-27}$ kg). Substituting the known values, we obtain

$$\mu_{Nucleus} = 5.05 \times 10^{-27} \, Am^2$$

From this discussion, it is evident that the nucleus spin magnetic momenta are smaller than those associated with electron.

Classification of magnetic materials: Based on the response of magnetic materials to external magnetic field, they are classified in to diamagnetic, paramagnetic and ferromagnetic materials. The ferromagnetic materials are further classified antiferromagnetic and ferromagnetic materials depending upon spinning orientation of electrons.
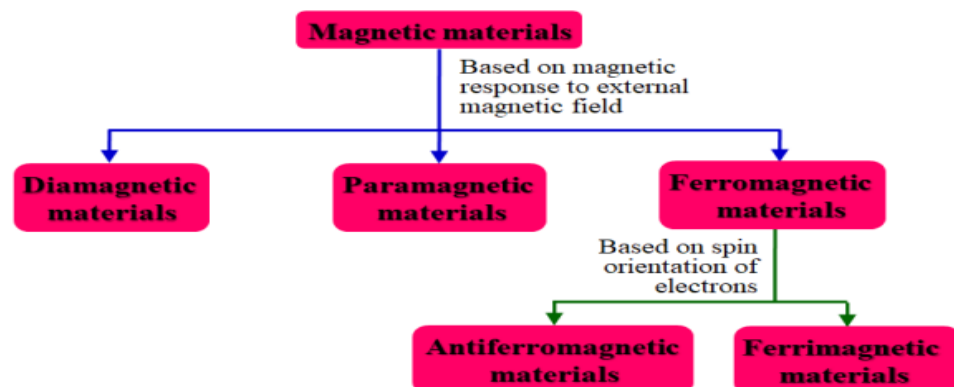
Property	Dia magnetic	Para magnetic	Ferro magnetics	Anti-Ferro magnetics	Ferri-magnetics
Phase / State	Found in solids, liquids and gases	Found in solids, liquids and gases	Found in solids only	Found in solids only	Found in solids only
Effect of magnet	Weakly repelled by a magnet	Weakly attracted by a magnet	(a) Strongly attracted by a magnet (b) Below T_C, spins are aligned parallel in magnetic domains 	(a) Strongly attracted by a magnet (b) Below TC, spins are aligned antiparallel in magnetic domains 	(a)Strongly attracted by a magnet (b) Below TC, spins are aligned antiparallel in magnetic domains
Behaviour under the absence of external field	No atomic dipole exists	Atomic dipoles with a net dipole moment exist	Atomic dipoles align themselves forming domains. Possess permanent magnetic moment.	Net magnetic moment becomes zero due to antiparallel alignment of spins.	Possess net magnetic moment due to uncompensated antiferromagnetism
Behaviour under external magnetic field	They do not preserve the magnetic properties once the external field is removed.	They do not preserve the magnetic properties once the external field is removed.	They preserve the magnetic properties even after the external field is removed.	Overall magnetization becomes zero	Possess net magnetic moment.
Permeability	Less than unity ($\mu < 1$)	Just higher than unity ($\mu > 1$)	Much higher than unity ($\mu \gg 1$)	Just higher than unity ($\mu > 1$)	Much higher than unity ($\mu \gg 1$)
Susceptibility	χ is negative and low	χ is positive and low	χ is positive and high	χ is positive and low	χ is positive and high
Temperature effect	No impact	They turn into diamagnetic as the temperature increases	They turn into paramagnetic above the Curie temperature	They turn into paramagnetic above the Curie temperature	They turn into paramagnetic above the Curie temperature
Examples	Copper (Cu), Silver (Ag), Gold (Au), etc	Aluminum (Al), Chromium (Cr), Manganese (Mn), etc.	Iron (Fe), Nickel (Ni), Cobalt (Co), etc.	MnO (Manganese oxide), FeO (Iron oxide), NiO (Nickel oxide)	Fe.Fe2O4 (Iron ferrite), Zn.Fe2O4 (Zinc ferrite), Ni.Fe2O4 (Nickel ferrite)

Ferrites:

The magnetic materials that exhibit spontaneous magnetization are known as ferrites. They can have a net magnetic moment even in the absence of external magnetic field due to uncompensated antiferromagnetism. They are capable of exhibiting both magnetic and electric properties. However, they are good electrical insulators. They filter noise in frequency over a broad frequency range and dissipate the noise energy in the form of heat.

Ferrites consists of ferric oxide (Fe_2O_3) combined with one or more oxides of divalent materials such as zinc, nickel etc. The general formula of ferrites is MFe_2O_4, where M indicates the divalent metallic element.

Examples are Iron ferrite ($FeFe_2O_4$ or Fe_3O_4, called magnetite or load stone), Zinc ferrite ($ZnFe_2O_4$), Nickel ferrite ($NiFe_2O_4$) etc.

Based on magnetic coercivity and the resistance to get demagnetized, they can be classified into two categories, namely soft and hard ferrites.

Soft ferrites: They can have low coercivity and their magnetism can change. Soft ferrites can act as conductors of magnetic fields. Examples are zinc, cobalt, nickel, manganese, and magnesium.

Hard ferrites: They can have high coercivity and their magnetism cannot change. They are used to make permanent magnets. Hard ferrites are composed of iron and barium or strontium oxides. They are widely used in household products such as refrigerator magnets.

Properties of ferrites:

(i) They have strong magnetic properties

(ii) They have high magnetic permeability

(iii) They have relatively low conductivity

(iv) They have low eddy currents

(v) They have low dielectric loss

Applications of ferrites:

(i) They are used to make efficient magnetic cores

(ii) They are used for high frequency inductors

(iii) They are used for transformer cores

(iv) They are used to make antenna cores in radio and TV communication

(v) They are used to make microwave components

Domain concept for ferromagnetism (OR) Weiss domain theory:

In 1907, Pierre Weiss proposed the domain theory to explain ferromagnetism and magnetic hysteresis of materials. The Postulates of domain theory are given below.

1. A ferromagnetic material is divided into a large number of small regions, called the domains.
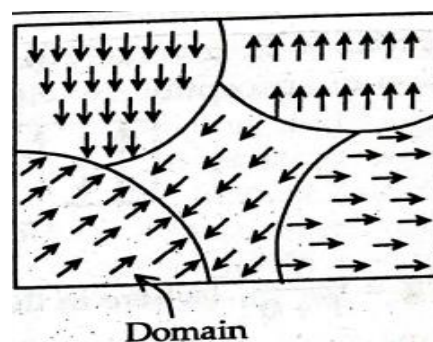
Domain

2. Each domain is spontaneously magnetized. That is, in each domain the atomic magnetic moments are in the same direction and the domain has a net magnetic moment.

3. The magnetic moment varies from domain to domain.

4. Two domains separate by domain wall or Bloch wall.

5. In the absence of external magnetic field, the net magnetization is zero due to random orientation of domains.

6. When an external magnetic field is applied to a ferromagnetic material, the magnetization is produced by two ways, (i) by the motion of domain walls and (ii) by the rotation of domains.

By the motion of domain walls: When a weak magnetic field is applied, then the area of

(a) Unmagnetised   (b) Boundary Displacement   (c) Domain Rotation
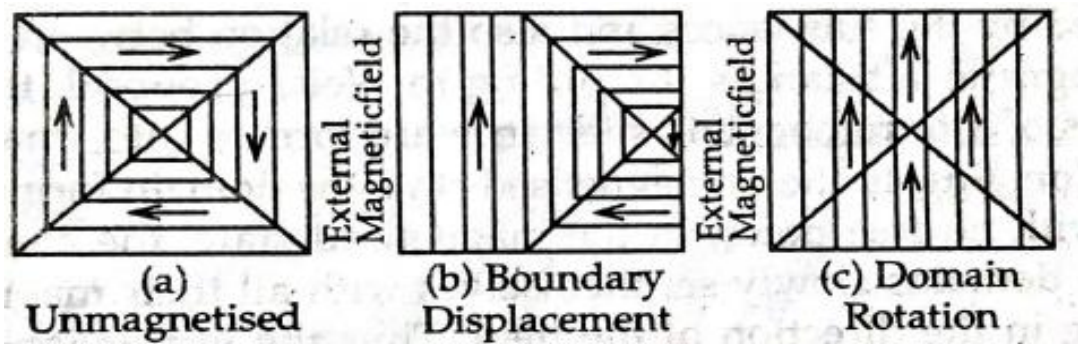
domains having dipoles parallel to the applied magnetic field increases by the motion of domain walls.

By the rotation domains: If the applied magnetic field is strong, then the domains are rotated parallel to the field direction by the rotation of domains

In the presence of strong applied magnetic field, the total internal energy of domain structure of a ferromagnetic material increases and it includes the following energies.

(i) Exchange energy (or) Magnetic field energy: The interaction energy which makes the adjacent dipoles align themselves is called exchange energy. It is also known as magnetic field energy. This energy arises from an interaction of electron spins and it depends upon the interatomic distance.

(ii) Crystalline anisotropy energy: The excess of energy required to magnetize a specimen along the hard direction is called the crystalline anisotropy energy.

(iii) Domain wall energy (or) Bloch energy: A thin boundary or region that separates adjacent domains in different directions is called domain wall or Bloch wall. The energy of domain wall is due to both exchange energy and anisotropic energy.

(iv) Magnetostriction energy: When a material is magnetized, it is found that it suffers a change in dimensions, called Magnetostriction. If the domains are magnetized in different

directions, they will either expand or shrink. So, some 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.

Domain walls (Qualitative):

An interface separating two magnetic domains is called the domain wall.

• The boundary between two neighbouring domains is also is called the domain wall.

• A domain wall is also called the Bloch wall.

• Domain is a transition between different magnetic moments and usually undergoes an angular displacement of 90° or 180°.

• A domain wall is a gradual reorientation of individual moments across a finite distance. Based on spin alignment domain walls are categorized into two types.
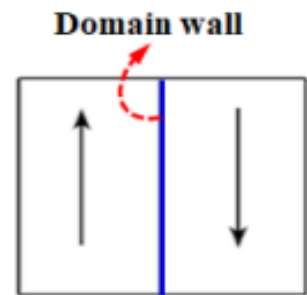
Thick or wide domain wall:

When the spins at the boundary are misaligned due to exchange energy and if the direction of spin changes gradually, then it leads to thick wall.
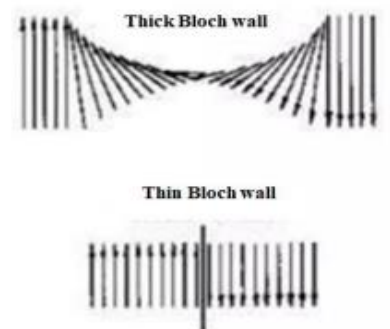
Thin or narrow domain wall:

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

Magnetic hysteresis or B-H curve:

When a ferromagnetic specimen is placed in a magnetic field, the specimen gets magnetized by the phenomenon of induction i.e., the alignment of domains along the applied magnetic field. Even the applied magnetic field is removed a part of domain alignment retained in the specimen. Thus, the material has become magnetized. The applied magnetic field intensity (H) is varied, the magnetic flux density (B) in the specimen vary non-linearly. The variation of B as a function of H is shown in the following figure.
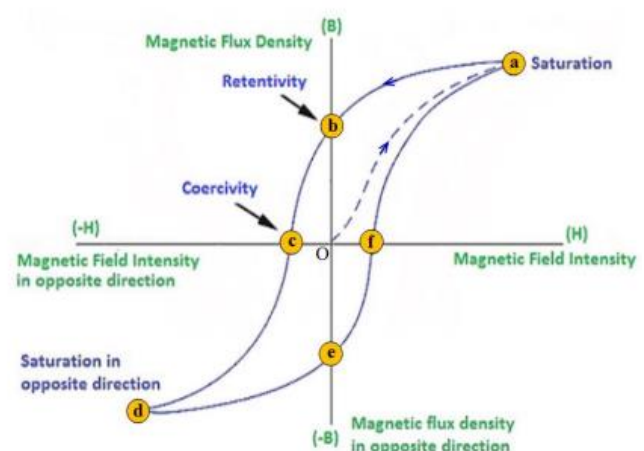
• In above figure the point „O" represents an initially un-magnetized point of the specimen and a zero magnetic intensity point.

• As H increases, B increase non-linearly and reaches to point „a", called the magnetic saturation point. At this point all most all the domains will align along the field direction.

• When H is reduced, the curve moves along the path „ab" and reaches to point „b", called the point of retentivity. In this case, some magnetic flux retained in the specimen even at H = 0.

• When H is increased in opposite direction the curve moves to the point „c", called the point of coercivity. At this point, the magnetic flux density becomes zero, i.e., B = 0

• As H is increased further the specimen will again magnetized in opposite direction up to the point „d", called the magnetic saturation point in opposite direction.

• If H is reduced, the curve moves along the path „defa" and finally reaches to the point „a", called the positive saturation point. This study clears that the magnetic flux density (B) always lags behind the magnetic field intensity (H). This lagging of B behind H is called the magnetic hysteresis.

Note:

Retentivity: The measure of residual magnetic flux in the specimen when the applied magnetic field is removed is known as retentivity or remanence.

Coercivity: The strength of magnetic field intensity required to remove the residual magnetism of the specimen is known as coercivity.

Applications of magnetic materials:

Magnetic materials are used in variety of playing toys.

They are used to make compass needles to know the earth directions.

They can be used in some medical scans such as NMR and MRI to create images of the bone structure, organs and tissues.

They are used to recycle the things in a faster way.

They are used in TV, Radio and telecommunication networks.

Some pieces of jewellery have magnetic clasps to clip the ends together around the neck.
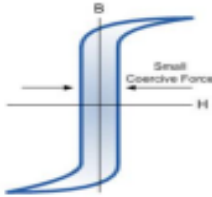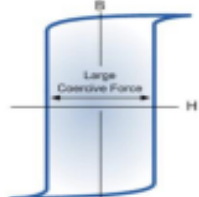
They can be used in consumer electronic devices such as microwaves, speakers, earphones, etc.

In computers data can be saved in hard drive that contains a powerful magnet.

Huge magnets are used to float Mag-Lev trains above the ground travelling at fast rate without friction

Soft and hard magnetic materials:

Based on the size of hysteresis curve, the magnetic materials are categorized into two types, namely soft magnetic materials and hard magnetic materials.

Property	Soft magnetic materials	Hard magnetic materials
Statement	Materials with narrow hysteresis loop are known as soft magnetic materials.	Materials with broad hysteresis loop are known as hard magnetic materials.
B-H curve		
Retentivity	Retentivity is low	Retentivity is high
Coercivity	Coercivity is low	Coercivity is high
Permeability (μ)	Permeability is high	Permeability is low
Susceptibility (χ)	Susceptibility is high	Susceptibility is low
Magnetization	They can be easily magnetized	They cannot be easily magnetized
Examples	Ferrites, Garnets, Metal alloys such as Fe-Si, Fe-Ni etc.	Metal alloys such as Al-Ni-Co, Ni-Steel (iron-carbon alloy), Chromium-Steel etc.
Use	They are used to make electromagnets	They are used to make permanent magnets
Applications	They find wide applications in (a) Transformer cores, (b) Telephone diaphragms, (c) Chokes, (d) Micro-wave isolators, (e) Switching circuits (f) Electromagnetic machinery etc.	They find wide applications in (a) Magnetic detectors, (b) Microphones, (c) Flux meters, (d) Voltage regulators, (e) Speedometers, (f) Sensors in automobiles etc.