

Applied Physics

Unit 5: Dielectric Materials & Magnetic Materials

Dr. G. Patrick

UNIT V

Dielectric Materials: Introduction, Types of polarizations: Electronic, Ionic and Orientation, Calculation of Electronic and Ionic polarizability, Internal fields in solids, Clausius-Mossotti equation, Applications of dielectric materials.

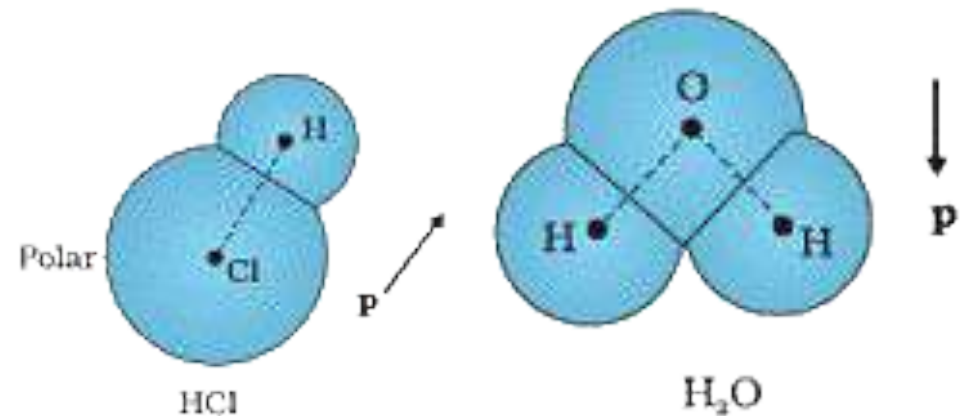
Magnetic Materials: Introduction, Bohr magneton, classification of magnetic materials: Ferro, Para, Dia, Antiferro and Ferri, Hysteresis curve based on domain theory, Soft and hard magnetic materials, Applications of magnetic materials.

Dielectric Materials

- Dielectric Materials are Insulators with no free electrons.
- When placed in electric field they are polarized.
- They are non-conductors of electricity with special properties in the presence of the electric field.
- Example: Glass, mica, polymers
- Dielectrics may be polar or non-polar

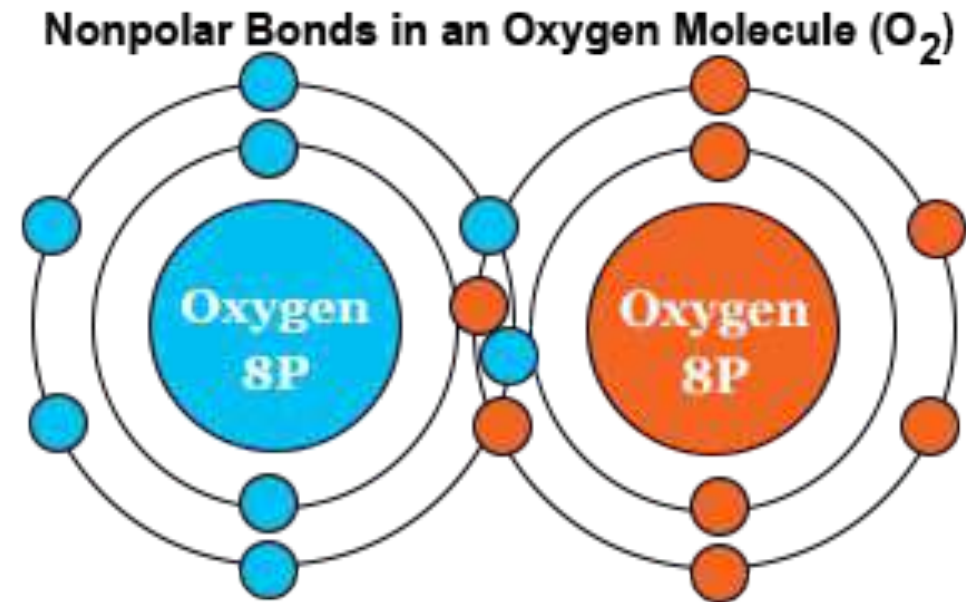
Polar dielectric

- A Polar molecule is one in which the centre of gravity of the positive charge is separated by a finite distance from the centre of gravity of the negative charge.
- They have permanent dipole moment.
- Polarization of molecule strongly depends on the temperature.
- Eg. HCl, H₂O



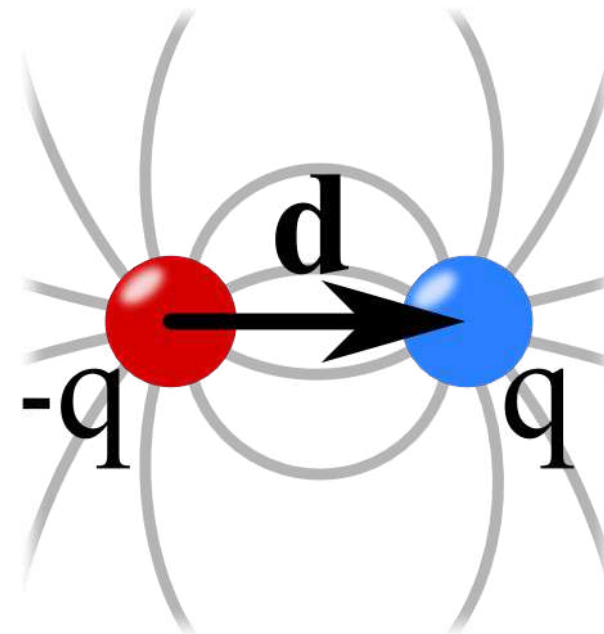
NonPolar dielectric

- A non polar molecule is one in which the centre of gravity of the positive charge and negative charge coincide.
- They do not have permanent dipole moment.
- The polarization of non-polar molecules is independent of temperature.
- Eg. Oxygen molecule, H_2 , N_2



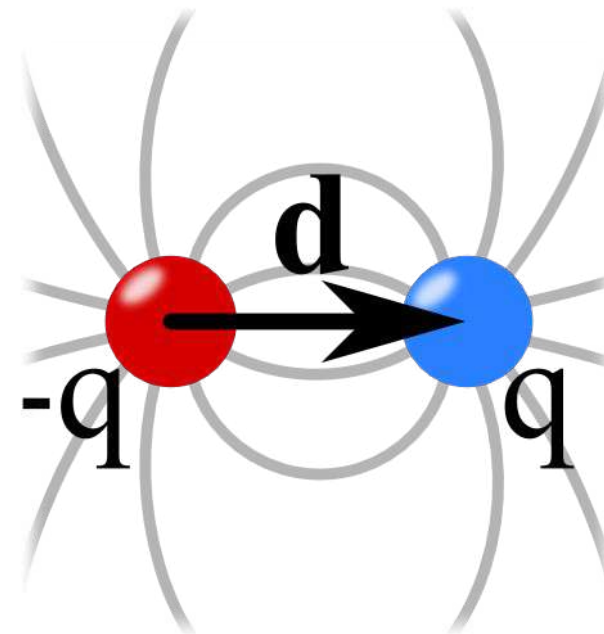
Electric dipole

- **Electric dipole:** Two equal and opposite charges small in magnitude and separated by a small distance constitute a electric dipole.
- It is a vector , the direction is from negative to positive charge.



Electric dipole moment

- It is the product of magnitude of charge and the distance between the two charges.
- $\mu = q * d$



Dielectric Constant or relative permittivity

- Dielectric constant is the ratio between the permittivity of the medium to permittivity of free space.

$$\epsilon_r = \frac{\epsilon}{\epsilon_o}$$

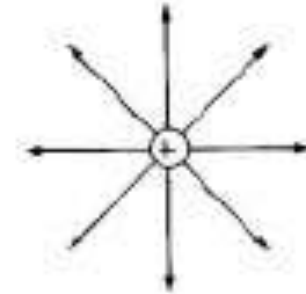
- It is also defined as the capacitance of the capacitor with dielectric to capacitance of the same capacitor without dielectric.

$$K = \frac{C}{C_0}$$

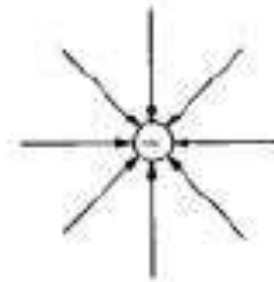
- It is a measure of the electric polarization in the dielectric material and it has no units.
- Materials with higher dielectric constant are easily polarized and behaves as good electrical insulators

Electric flux

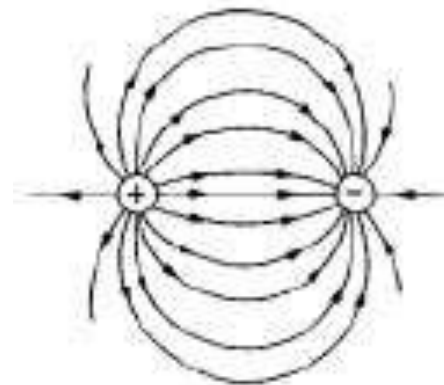
- Electric field is the space around a charge where its influence can be felt.
- Electric flux($\Phi = \Phi$) is the total number of electric field lines coming out from a charge. Measured in Columb.



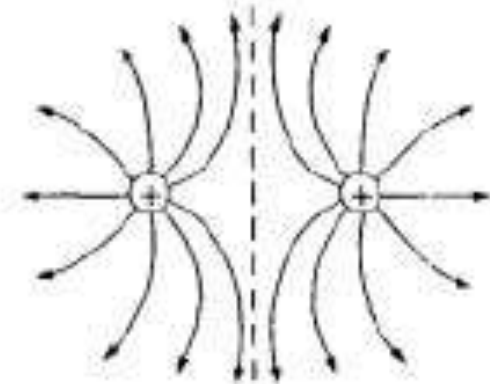
(a) Positive charge



(b) Negative charge



(c) Positive and negative charge



(d) Positive and positive charge

Electric flux density & electric susceptibility

- Electric flux density or displacement vector (**D**) is the normal (Perpendicular) flux per unit area.

- $\mathbf{D} = \frac{\Phi}{A}$ Unit is C m^{-2}

- $\mathbf{D} = \epsilon \mathbf{E}$, Where E is the electric field strength and $\epsilon = \epsilon_0 \epsilon_r$

therefore $\mathbf{D} = \epsilon_0 \epsilon_r \mathbf{E}$ ----- (1)

- In a dielectric material, polarization occurs, and the flux density has the value given by

$\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P}$ ----- (2) where P is the polarization vector

From equ. 1 and 2

- $\epsilon_0 \epsilon_r \mathbf{E} = \epsilon_0 \mathbf{E} + \mathbf{P}$

- $\mathbf{P} = \epsilon_0 \mathbf{E}(\epsilon_r - 1)$

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Types of Polarization

- Polarization occurs due to several atomic mechanisms. When the specimen is placed inside electric field, mainly three types of polarizations are possible. These are
 - Electronic Polarization
 - Ionic Polarization or Atomic Polarization
 - Orientational or Dipolar polarization

Electronic polarization

- • Electric flux density or displacement vector (**D**) is the normal (Perpendicular) flux per unit area.

- $\mathbf{D} = \frac{\Phi}{A}$ Unit is C m⁻²

- $\mathbf{D} = \epsilon \mathbf{E}$, Where E is the electric field strength and $\epsilon = \epsilon_0 \epsilon_r$

therefore $\mathbf{D} = \epsilon_0 \epsilon_r \mathbf{E}$ ----- (1)

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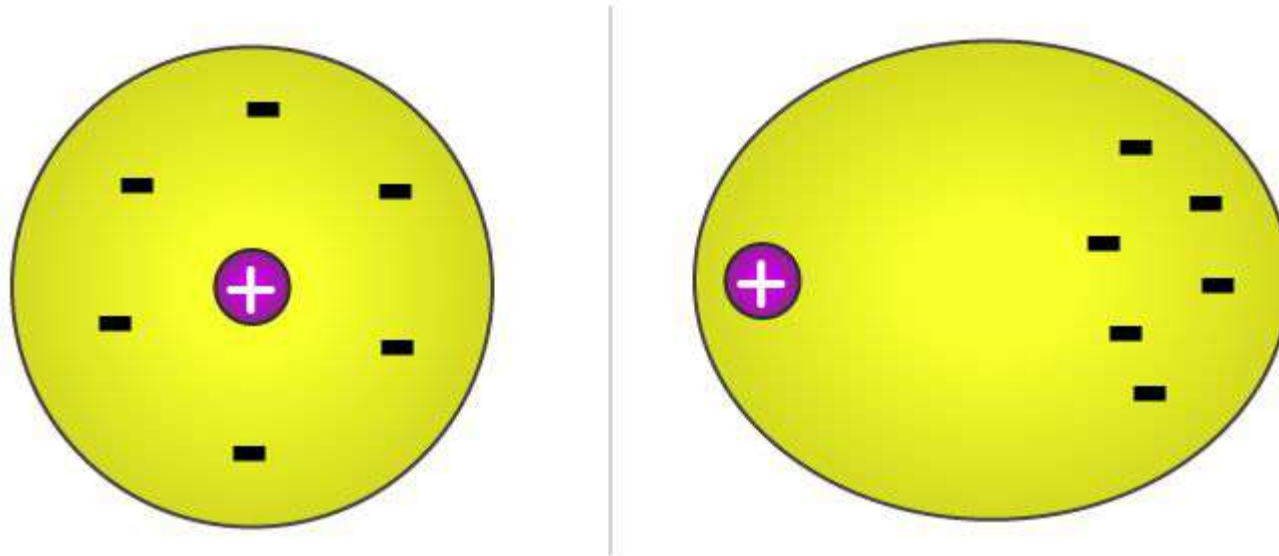
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From equ. 1 and 2

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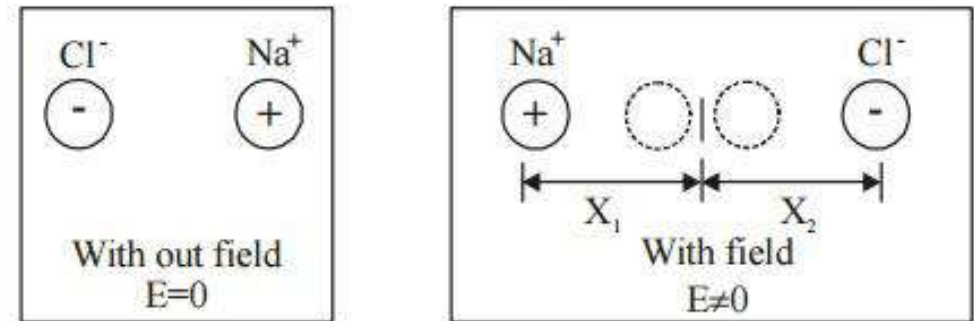
- $\mathbf{P} = \epsilon_0 \mathbf{E} (\epsilon_r - 1)$

Electronic polarization



Ionic or Atomic Polarization

- When an electric field is applied to an ionic crystal, the polarization that arises due to the displacement of the positive ions away from the field and the displacement of the negative ions towards the field is known as ionic polarization.
- This type of polarization occurs in ionic molecules such as NaCl, KBr, KCl and LiBr.



Ionic Polarization

- Electric flux density or displacement vector (**D**) is the normal (Perpendicular) flux per unit area.

- $D = \frac{\Phi}{A}$ Unit is $C\ m^{-2}$

- $D = \epsilon E$, Where E is the electric field strength and $\epsilon = \epsilon_0 \epsilon_r$

therefore $D = \epsilon_0 \epsilon_r E$ ----- (1)

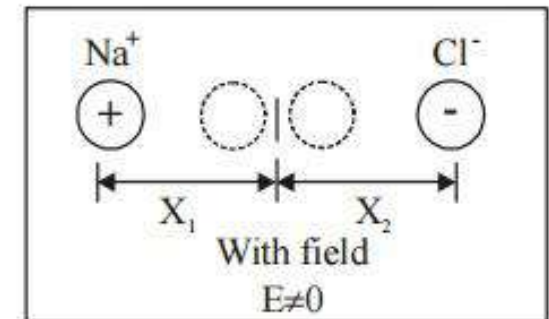
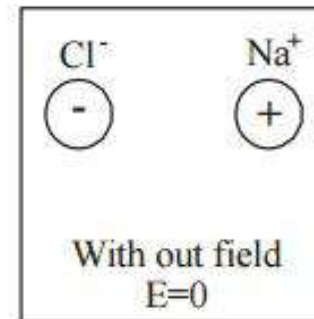
- In a dielectric material, polarization occurs, and the flux density has the value given by

$D = \epsilon_0 E + P$ ----- (2) where P is the polarization vector

From equ. 1 and 2

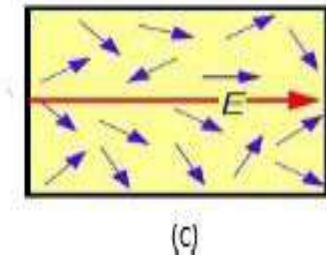
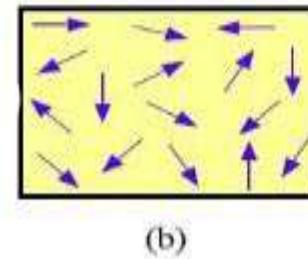
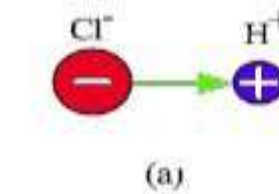
- $\epsilon_0 \epsilon_r E = \epsilon_0 E + P$

- $P = \epsilon_0 E (\epsilon_r - 1)$



Orientation or Dipolar Polarization

- The Orientation or dipolar polarization is produced only in polar molecules like HCl, H₂O and Nitrobenzene.
- When an electric field is applied to a polar molecule, the dipole experience a torque and try to align parallel to the applied field, which results in a rotation of the dipole.
- Orientation polarizability is inversely proportional to temperature.



Electronic Polarization

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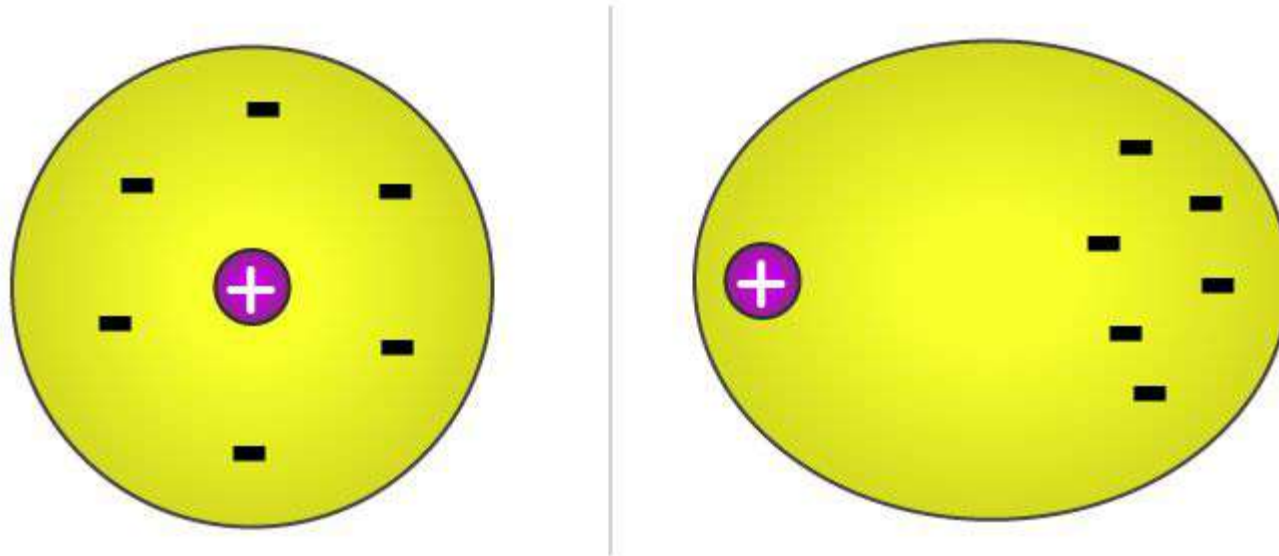
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From equ. 1 and 2

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Electronic polarization



Electronic Polarization

Calculation of electronic polarizability:

- (I) Without Electric field:
- Let us consider a classical model of an atom. Assume the charge of the nucleus is $+Ze$ and the nucleus is surrounded by an electron cloud of charge $-Ze$, which is distributed in sphere of radius R .
- The charge density of the sphere = $\frac{-Ze}{\frac{4}{3}\pi R^3}$
- Charge density $\rho = \frac{-3}{4} \frac{Ze}{\pi R^3}$ --- (1)

Electronic Polarization

With Electric field:

- When the dielectric is placed in an electric field E , two phenomena occurs
- Lorentz force due to the electric field tends to separate the nucleus and the electron cloud from their equilibrium position.
- After the separation, an attractive coulomb force arises between the nucleus and electron cloud which tries to maintain the original equilibrium position.
- At equilibrium Lorentz force = Coulomb force and let x be the displacement made by the electron cloud from the positive core .

Electronic Polarization

- At equilibrium Lorentz force = Coulomb force
- Lorentz force = charge * field = $-ZeE$ -----2
- Coulomb force = charge * field = $+Ze * \frac{Q}{4\pi\epsilon_0 x^2}$
- Q is the charge enclosed in a sphere of radius x
- Q = charge density of the electron * volume of the sphere

Electronic Polarization

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

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

- Coulomb force = $+Ze * \frac{Q}{4\pi\epsilon_0 x^2}$

- Substitute the value of Q

Electronic Polarization

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

- At equilibrium Lorentz force = Coulomb force

- Equate equ. (2) and (3)

$$-ZeE = \frac{Ze}{4\pi\epsilon_0 x^2} * - \frac{Zex^3}{R^3}$$

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

Electronic Polarization

- Induced dipole moment = magnitude of charge * displacement = $Ze * X$

- $\mu_e = Ze * \frac{4\pi\epsilon_0 R^3 E}{Ze}$

- $\mu_e = 4\pi\epsilon_0 R^3 E$

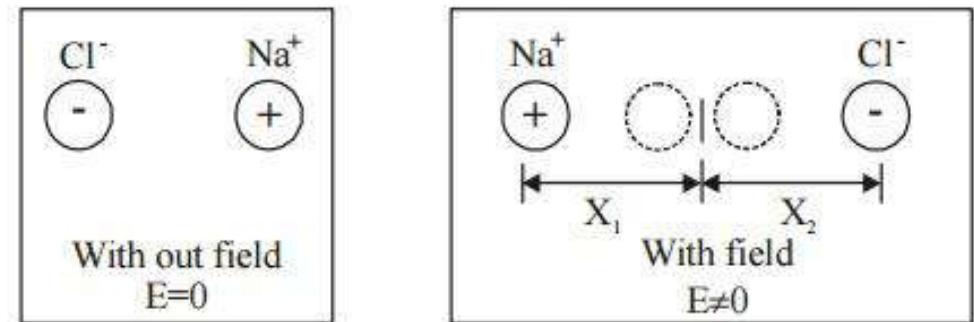
- $\mu_e = \alpha_e * E$

- where $\alpha_e = 4\pi\epsilon_0 R^3$

- This is called electronic polarizability

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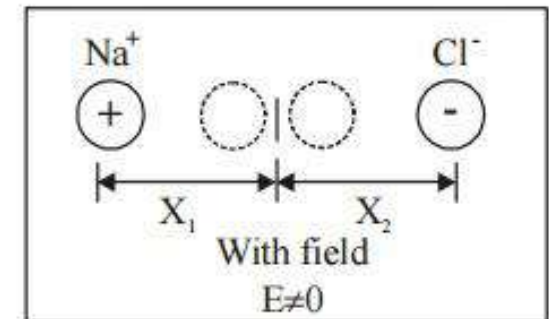
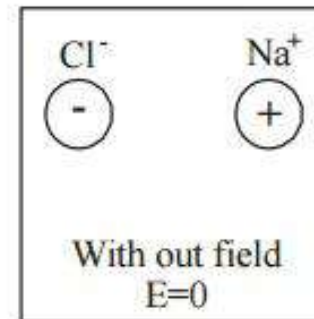
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Numericals: Dielectric material

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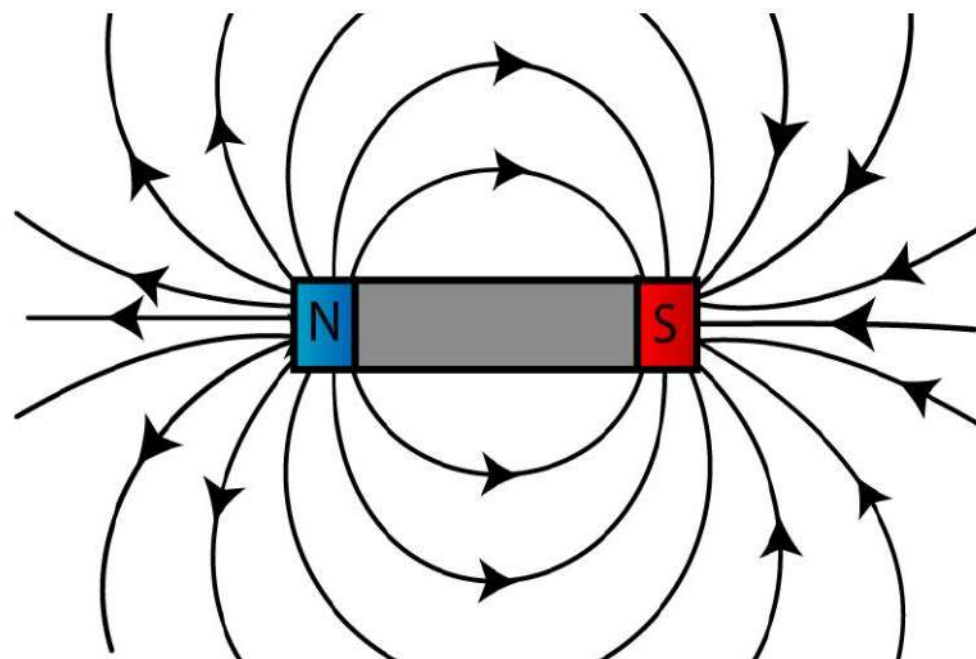
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Magnetic Materials

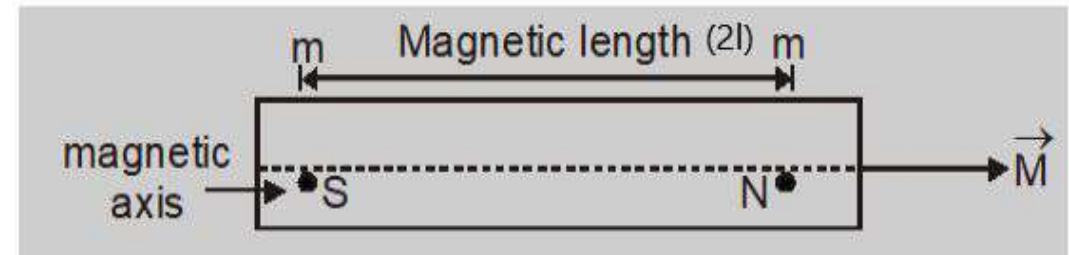
Magnetic field

- Magnetic field: The region around a magnet in which it exerts forces on other magnets or on other magnetic material is called a magnetic field.
- Magnetism arises from the Magnetic dipole of Magnetic Materials.



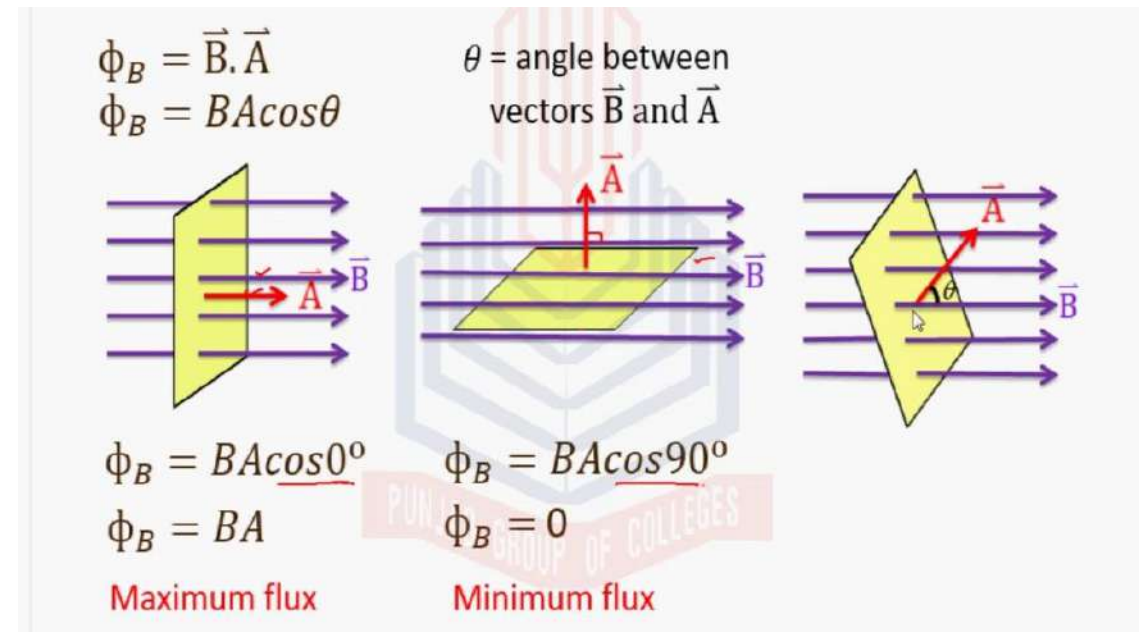
Magnetic dipole

- A pair of magnetic poles of equal and opposite strengths separated by a finite distance is called a magnetic dipole.
- The magnitude of dipole moment is the product of the pole strength ' m ' and the separation ' $2l$ ' between the poles.
- $\mathbf{M} = m \cdot 2l$ Units: Am^2
- The direction of the dipole moment is from South pole to North Pole along the axis of the magnet.



Magnetic flux (ϕ)

- Magnetic flux(ϕ) [phi] is defined as the number of magnetic field lines passing through a given closed surface. It provides the measurement of the total magnetic field that passes through a given surface area.
- Units: Weber (Wb)



Magnetic Induction or Magnetic flux Density(B)

- The number of field lines passing through a unit area of cross-section is called magnetic induction or magnetic flux density.
- $B = \Phi/A$ Units: wb/m² or Tesla.

Magnetic field intensity or strength (H)

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

Units : A/m

- $B = \mu H$ where μ is the permeability of the medium.
- Permeability is a material property which describes the ease with which the magnetic field lines can pass through the material. Units: henry/meter.

Intensity of magnetization(I)

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Origin of Magnetic Moment

- In atoms, the permanent magnetic moments can arise due to:
 1. the orbital magnetic moment of the electrons
 2. the spin magnetic moment of the electrons and
 3. the spin magnetic moment of the nucleus.

Orbital magnetic moment of the electrons & Bohr magneton

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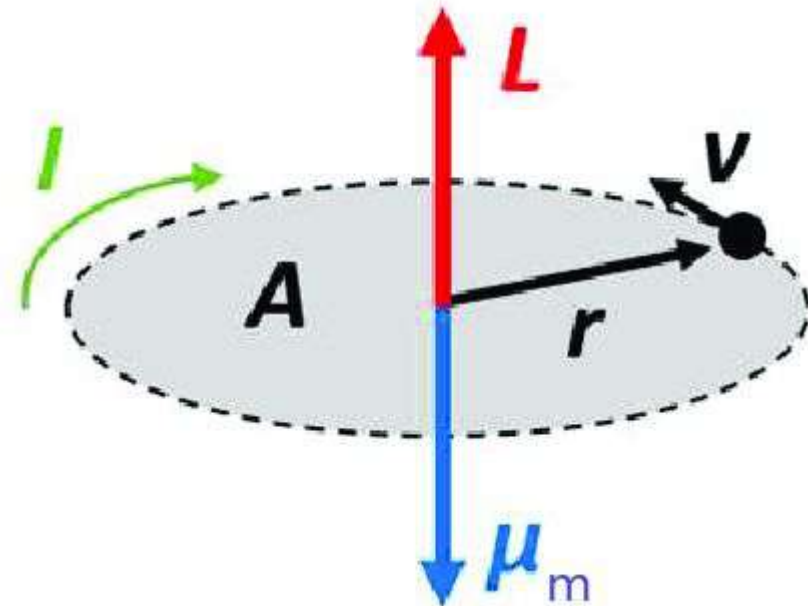
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Orbital magnetic moment of the electrons & Bohr magneton

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Spin magnetic moment of electron and nucleus

Electron spin: Each electron spins about an axis through itself and this gives rise to a magnetic dipole moment.

- The major contribution to atomic magnetic moment comes from the spin of unpaired valence electrons. The magnetic moments due to electron spin align in different directions to generate a non zero magnetic moment. When placed in a magnetic field, the atomic dipoles are aligned with their directions of magnetic moment along the direction of external field.

Nuclear spin: In addition to the contribution of electrons, the nuclear spin also contributes to magnetic moment of atoms. The contribution is negligible.

- In general, the total magnetic moment of an atom is the sum of the orbital and spin magnetic moments of its electrons.

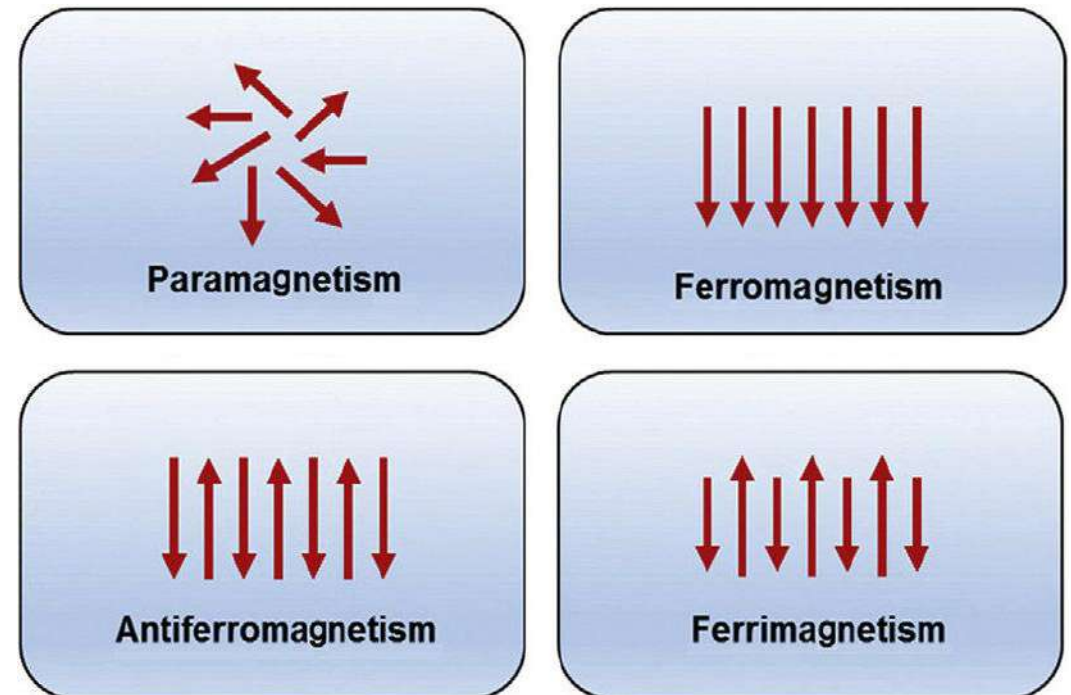
Classification of Magnetic Materials

Magnetic materials may be classified based on the atomic dipoles and the interactions between them.

- If the atoms of the materials do not have permanent magnetic dipoles, they are called as diamagnetic material.
- If the atoms of the materials have permanent magnetic dipoles, they may be paramagnetic, ferromagnetic, antiferromagnetic or ferrimagnetic, depending on the interaction between the individual dipoles.

Classification of Magnetic Materials

- In paramagnetic materials, the interaction between the atomic magnetic dipoles is negligible.
- In ferromagnetic materials the interaction between atomic magnetic dipoles is strong and they are aligned parallel to each other.
- If the neighbouring dipoles orient in opposite directions and if the dipoles are of equal magnitude, the material is antiferromagnetic.
- If the neighbouring dipoles are of different magnitude and oriented antiparallel, the material is ferrimagnetic.



Diamagnetism

- Diamagnetism occurs in materials whose atoms have even number of electrons i.e. electrons are paired.
- Due to different orientations of various orbits of an atom, the net magnetic moment is zero.
- When an external magnetic field is applied the motion of electrons in their orbits changes resulting in induced magnetic moment in a direction opposite to the direction of external field.

Properties:

- Permanent dipoles are absent.
- Weak repulsion is the characteristic property of diamagnetism.
- Relative permeability is less than one but positive.
- The magnetic susceptibility is negative and small. It is not affected by temperature.
- When placed inside a magnetic field, magnetic lines of force are repelled.
- Examples: Copper, Zinc, Bismuth, Silver, Gold

Paramagnetism

- Paramagnetism occurs in materials whose shells are unfilled and hence have net magnetic moment.
- In the absence of external magnetic field the net moments of the atoms are arranged in random directions and hence magnetization is zero.
- When external field is applied, the dipoles align in the direction of the field giving rise to induced positive dipole moment.

Properties:

- Paramagnetic material have permanent magnetic dipoles.
- The magnetic susceptibility is small and positive and is inversely proportional to absolute temperature i.e. $\chi = C/T$. This is called Curie law, C is called Curie constant.
- Spin alignment is random.
- When placed inside a magnetic field it attracts the magnetic lines of force.
- Examples: Aluminum, Manganese, oxygen

Ferromagnetism

- Ferromagnetism arises when the magnetic moments of adjacent atoms are arranged in a regular order i.e. all pointing in the same direction.
- These substances possess a magnetic moment even in the absence of the applied magnetic field and is known as the spontaneous magnetization.
- There is a special form of interaction called “exchange “coupling occurring between adjacent atoms, coupling their magnetic moment together in rigid parallelism.

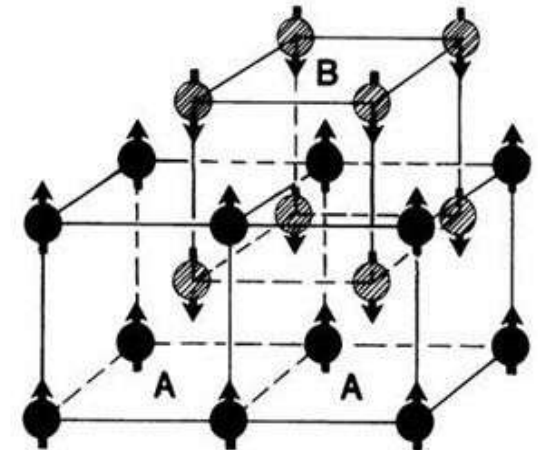
Ferromagnetism

Properties:

- Ferromagnetism is due to the existence of magnetic domains which can be spontaneously magnetized.
- In ferromagnetic materials, large magnetization occurs in the direction of the field.
- Strong attraction is the characteristic property of ferromagnetism.
- They exhibit spontaneous magnetization.
- The relative permeability is very high for Ferro magnetic.
- The magnetic susceptibility is positive and very high.
- Exhibit hysteresis phenomenon.
- When placed inside a magnetic field they attract the magnetic lines of forces very strongly.
- Examples: Iron, Nickel, Cobalt.

Antiferromagnetism

- Antiferromagnetism arises in materials in which the magnetic moments are equal, but adjacent magnetic moments point in opposite directions.
- An antiferromagnetic unit cell can be considered as composed of two interpenetrating ferromagnetic sublattices, say A and B as shown in the figure.
- The spin of A and B are oriented in opposite directions.

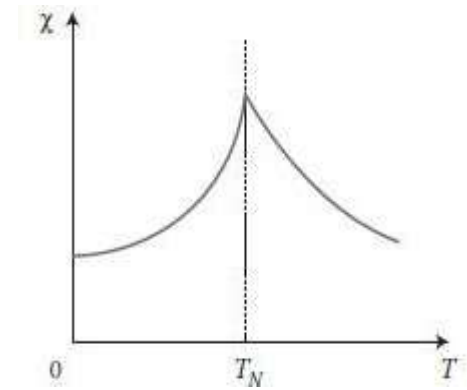


Antiferromagnetism

- When there is no external magnetic field acting on them, the net magnetization is zero.
- When placed in a external magnetic field and the temperature is zero, the magnetization is still zero.
- As temperature is increased in the presence of external magnetic field, the antiparallel arrangement of spins is slowly disturbed and magnetization(and hence susceptibility) increases.
- The susceptibility reaches a maximum at Neel temperature, T_N .
- At Neel temperature, the spin ordering is lost completely.

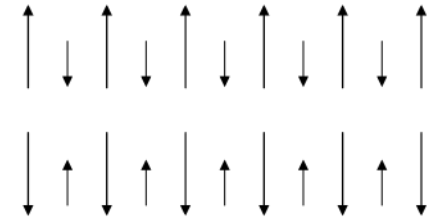
Antiferromagnetism

- The susceptibility decreases with further increase in temperature and the material becomes paramagnetic above the Neel temperature.
- The elements manganese and chromium exhibit ferromagnetism at room temperature.
- Most of the antiferromagnetic materials are compounds. Eg. MnO



Ferrimagnetism

- In certain crystals the magnetic moment of the two sublattices are not exactly equal in magnitude and they are oriented in opposite directions. They have a resultant magnetic moment.



- They possess spontaneous magnetization.
- Ferrimagnetic materials are very similar to ferromagnetic materials in their macroscopic magnetic characteristics.
- Ferrimagnetic materials are widely used in high frequency applications where ferromagnetic materials cannot be utilized.

Ferrimagnetism

Ferrites:

- Ferrimagnetic materials are ceramic materials and are therefore good electrical insulators. The most important group of these materials is ferrites. Garnets constitute another important group.
- Ferrites consists of ferric oxide Fe_2O_3 , combined with one or more oxides of divalent metals. They are represented by a general formula $\text{M Fe}_2\text{O}_4$ or $\text{M.O.Fe}_2\text{O}_3$ in which M represents a metallic element.
- Example of ferrite is magnetite $\text{FeO.Fe}_2\text{O}_3$
- Garnets have a very complicated crystal structure and the general formula is $\text{M}_3\text{Fe}_5\text{O}_{12}$ where M represents a rare earth ion such as samarium, yttrium etc.

Ferrimagnetism

Applications of ferrites:

- They are used to produce ultrasonic frequency by magnetization principle.
- Ferrites are used in audio and video transformers.
- Ferrites rods are used in radio receivers to increase the sensitivity.
- Ferrites are used in computers and data processing circuits.
- Ferrites are used in switching circuits and in storage devices of computers.

Hysteresis curve based on domain theory

Domain theory of ferromagnetism

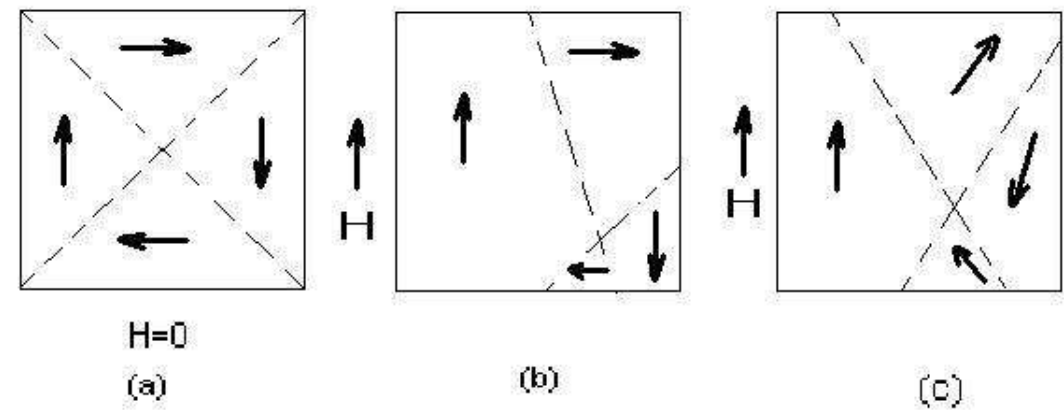
- According to Weiss, the specimen of ferromagnetic material have number of regions or domains which are spontaneously magnetized. In each domain spontaneous magnetization is due to parallel alignment of all magnetic dipoles.
- The direction of spontaneous magnetization varies from domain to domain.
- The resultant magnetization may hence be zero or nearly zero.

Hysteresis curve based on domain theory

- When an external field is applied there are two possible ways for the alignment of domains.

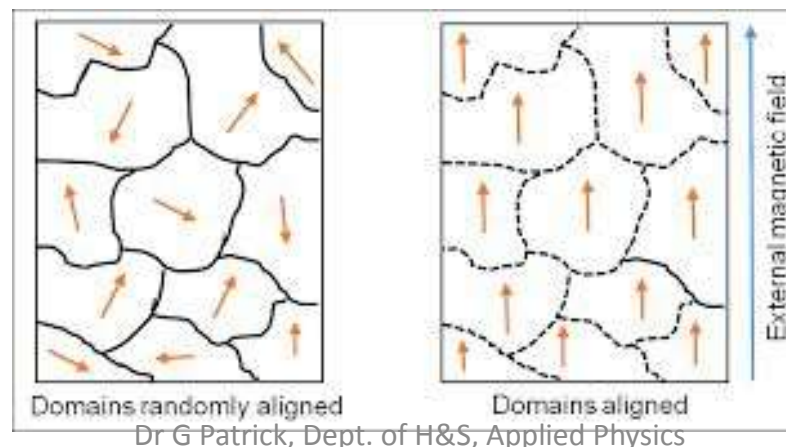
(i) **By motion of domain walls:** The volume of domains that are favorably oriented with respect to the magnetizing field increases at the cost of those that are unfavorably oriented. Shown in fig (b).

(ii) **By rotation of domains:** when the applied magnetic field is strong, rotation of the direction of magnetization occurs in the direction of the field. Shown in fig (c).



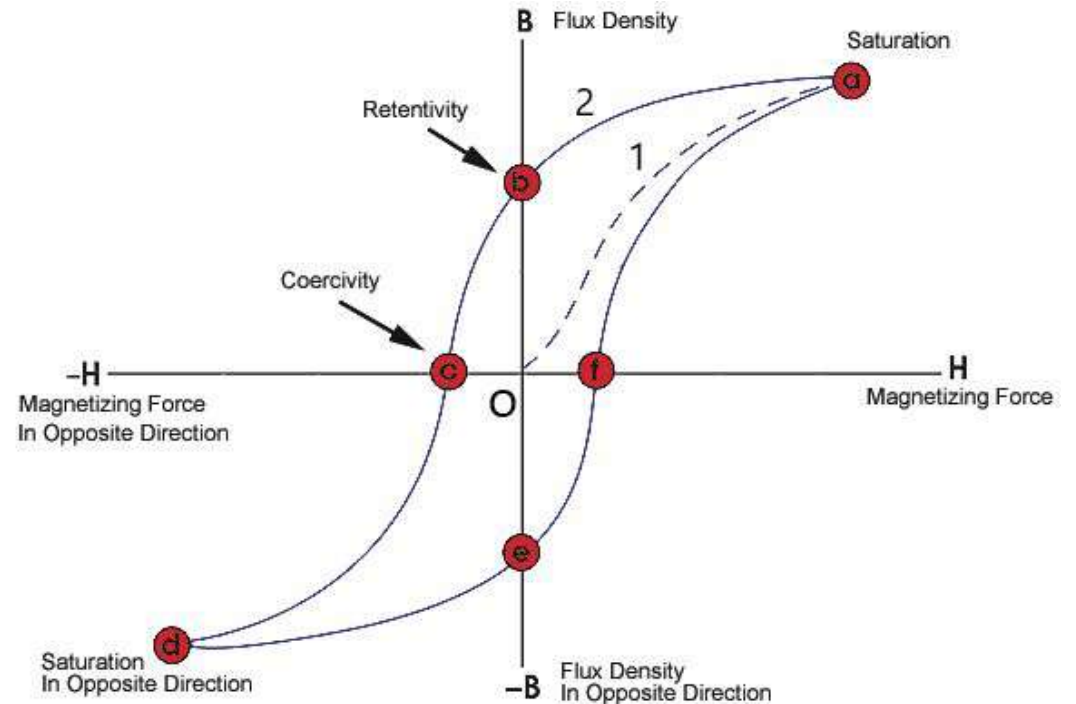
Hysteresis curve based on domain theory

- Hysteresis: The hysteresis of ferromagnetic materials refers to the lag of magnetization behind the magnetising field.
- In the absence of a magnetic field, the domains in the material are randomly oriented and the resultant magnetic moment is zero.
- When an external magnetic field is applied, the domains get oriented in the direction of the external field.



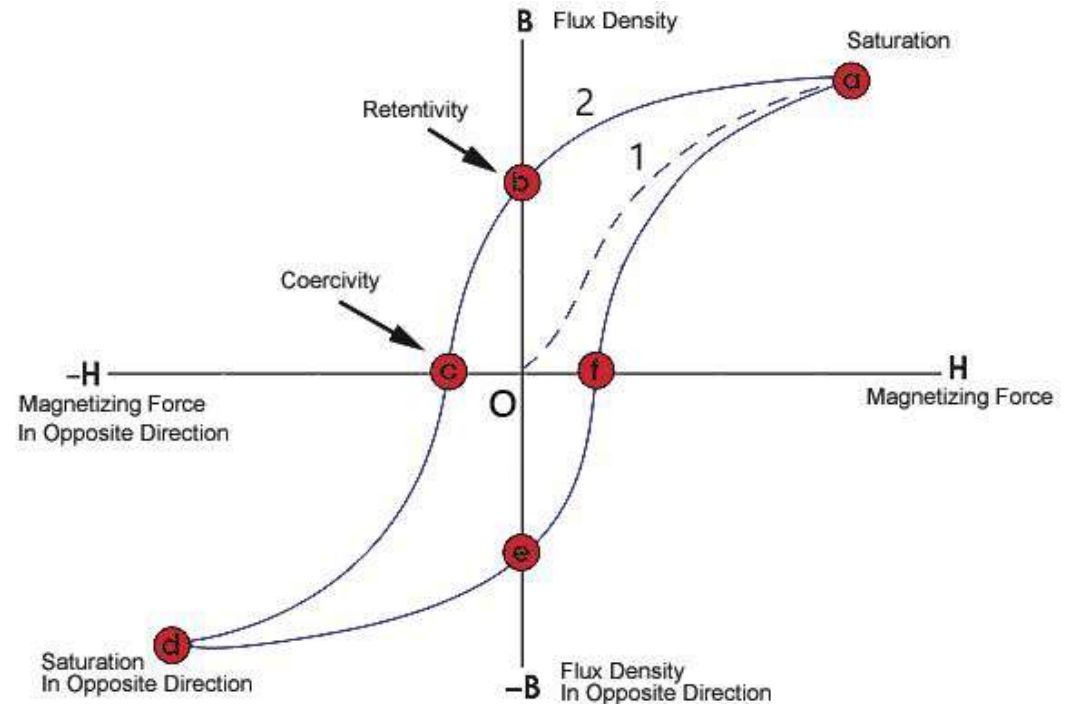
Hysteresis curve based on domain theory

- As the external magnetic field (H) is increased, the magnetization of the material proceeds along path 1 from o to a .
- Point ' a ' indicates saturation of magnetization i.e. all the domains are oriented in the direction of the external magnetic field.
- When the external magnetic field is reduced back to zero, the magnetization curve takes path 2 i.e. from ' a ' to ' b '.



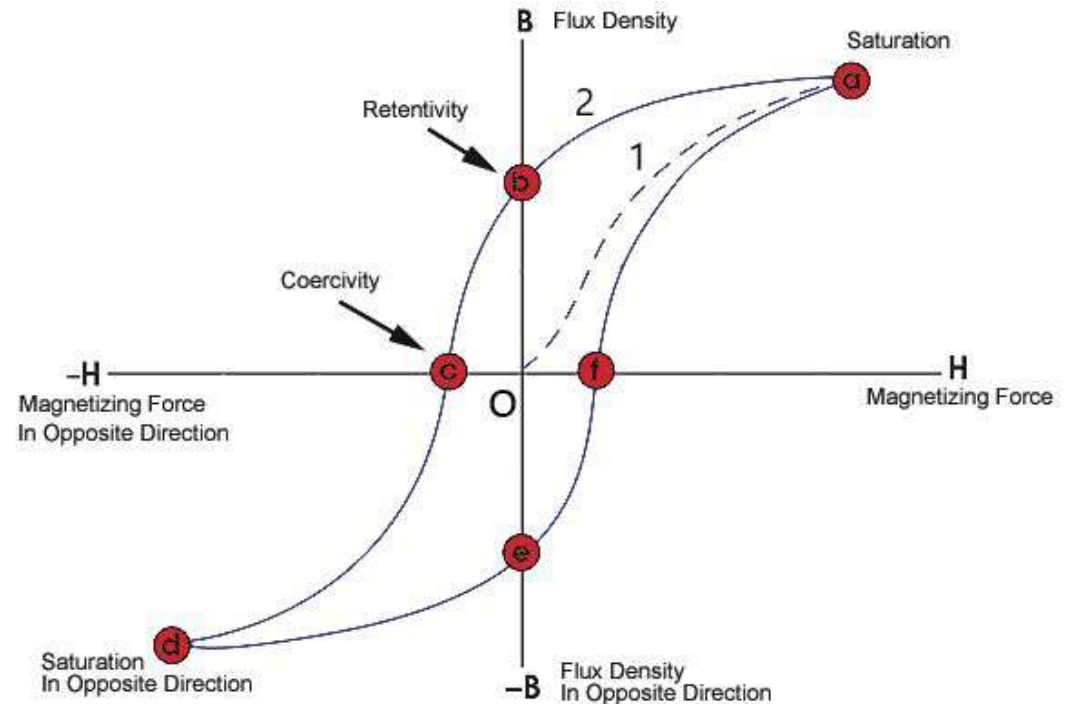
Hysteresis curve based on domain theory

- The original path 1 is not traced because of irreversible processes occurring in the course of demagnetization.
- Defects such as impurity atoms, dislocations and nonmagnetic inclusions present in the material effect the motion of domain walls.
- Domains retain their original orientation even when $H = 0$, leading to remnant induction B_r (Point 'b').



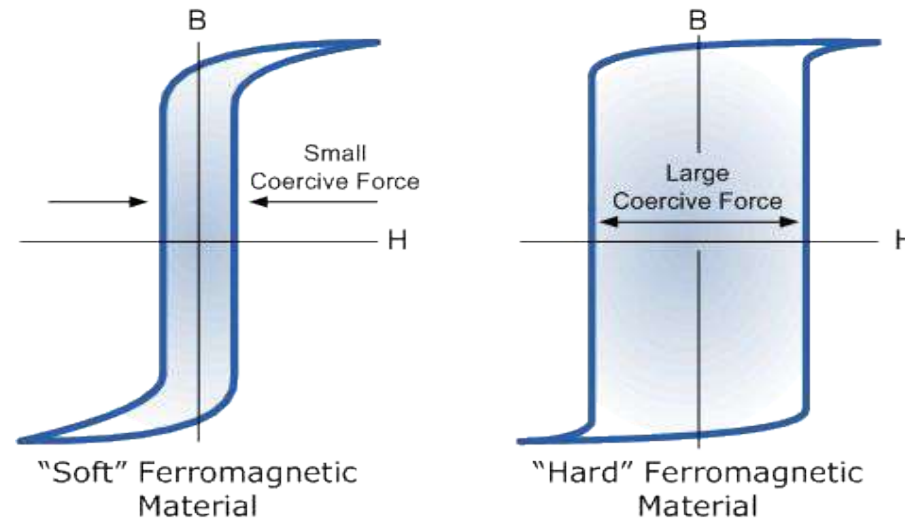
Hysteresis curve based on domain theory

- Elimination of the remanent magnetization(point 'c') requires the applied field $H (=H_c)$ in opposite direction.
- The amount of energy spent to reduce the magnetization (B) to zero is called “coercivity”
- Point 'd' indicates the saturation in the opposite direction.
- Hysteresis loss: It is the loss of energy in taking a ferromagnetic body through a complete cycle of magnetization and this loss is represented by the area enclosed by the hysteresis loop.



Soft and hard magnetic material

- The process of magnetization of a Ferro or Ferri magnetic material consist of moving domains walls so that favorably oriented domains grow. If the domain walls are easy to move and coercive field is low and the material is easy to magnetize. Such a material is called soft magnetic material.
- If it is difficult to move the domain walls, the coercive field is large then the material is magnetically hard .These are called hard magnetic material.



Soft and Hard magnetic materials

Soft magnetic materials

- Soft magnetic materials have low hysteresis loss due to small hysteresis loop area
- In these materials the domain wall movement is relatively easier, even for small changes in the magnetizing field the magnetization changes by large amount
- The coercivity and retentivity are small. Hence these materials can be easily magnetized and demagnetized.

Hard magnetic materials

- Hard magnetic materials have large hysteresis loss due to large hysteresis loop area.
- In these materials the domain wall movement is difficult because of presence of impurities and crystal imperfection and it is irreversible in nature.
- The coercivity and retentivity are large. Hence these materials cannot be easily magnetized and demagnetized

Soft and Hard magnetic materials

Soft magnetic materials

- These materials are free from irregularities; the magneto static energy is small.
- These materials have large values of susceptibility and permeability.
- These are used to make electronic magnets.
- Applications: Mainly used in electromagnetic machinery and transformer cores.

Hard magnetic materials

- In these materials, because of the presence of impurities and crystal imperfection the mechanical strain is more. Hence magneto static energy is large.
- These materials have small values of susceptibility and permeability
- These are used to make permanent magnets
- Applications: For production of permanent magnets used in magnetic detectors, microphones flux meters and loud speakers.

Numericals: Magnetic material

- Electric flux density or displacement vector (**D**) is the normal (Perpendicular) flux per unit area.

- $\mathbf{D} = \frac{\Phi}{A}$ Unit is C m^{-2}

- $\mathbf{D} = \epsilon \mathbf{E}$, Where E is the electric field strength and $\epsilon = \epsilon_0 \epsilon_r$

therefore $\mathbf{D} = \epsilon_0 \epsilon_r \mathbf{E}$ ----- (1)

- In a dielectric material, polarization occurs, and the flux density has the value given by

$\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P}$ ----- (2) where P is the polarization vector

From equ. 1 and 2

- $\epsilon_0 \epsilon_r \mathbf{E} = \epsilon_0 \mathbf{E} + \mathbf{P}$

- $\mathbf{P} = \epsilon_0 \mathbf{E} (\epsilon_r - 1)$