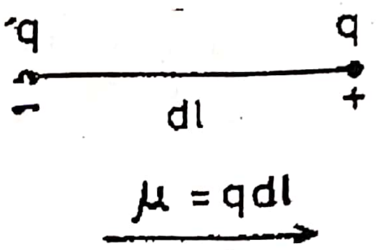
UNIT-4

[illegible]. DIELECTRIC PROPERTIES

Introduction: Dielectrics are insulating materials. In dielectrics, all the electrons are bound to their parent molecules and there are no free charges. Even with normal voltage or thermal energy, electrons are not released.

Electric Dipole: A system consisting of two equal and opposite charges separated by a distance is called electric dipole.



Dipole moment: The product of charge and distance between two charges is called dipole moment.

$$\text{i e, } \mu = q \times dl$$

Permittivity: It is a quantity, which represents the dielectric property of a medium. Permittivity of a medium indicates the easily Polarisable nature of the material.

Units: Faraday / Meter or Coulomb / Newton-meter.

Dielectric constant: The dielectric characteristics are determined by the dielectric constant. The dielectric constant or relative permittivity of a medium is defined as the ratio between the permittivity of the medium to the permittivity of the free space.

$$\varepsilon_r = \varepsilon / \varepsilon_0 = C / C_0 \quad \text{where}$$

ε is permittivity of the medium
ε_0 is permittivity of the free space
C is the capacitance of the capacitor with dielectric
C_0 is the capacitance of the capacitor without dielectric

Units: No Units.

Capacitance: The property of a conductor or system of conductor that describes its ability to store electric charge.

$$C = q / V = A\varepsilon / d \quad \text{where}$$

C is capacitance of capacitor
q is charge on the capacitor plate

V is potential difference between plates
A is area of capacitor plate
ε is permittivity of medium
d is distance between capacitor plates

Units: Farad .

✓**Polarizability (α) :** When the strength of the electric field E is increased the strength of the induced dipole μ also increases . Thus the induced dipole moment is proportional to the intensity of the electric field.

$\mu = \alpha E$ where α the constant of proportionality is called polarizability .It can be defined as induced dipole moment per unit electric field.

$$\alpha = \mu / E$$

Units: Farad – meter^2

✓**Polarization Vector (P) :** The dipole moment per unit volume of the dielectric material is called polarization vector **P** .if μ is the average dipole moment per molecule and N is the number of molecules per unit volume then polarization vector

$$P = N\mu$$

The dipole moment per unit volume of the solid is the sum of all the individual dipole moments within that volume and is called the polarization of the solid.

✓**Electric Flux Density or Electric Displacement (D):** The Electric Flux Density or Electric Displacement at a point in the material is given by

$$D = \varepsilon_r \varepsilon_0 E \text{ -------------(1) where}$$

E is electric field strength
ε_r is relative permittivity of material
ε_0 is permittivity of free space

As polarization measures additional flux density arising from the presence of the material as compared to free space, it has same units as D.

Hence $D = \varepsilon_0 E + P$ -----------(2)

Since $D = \varepsilon_0 \varepsilon_r E$

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

$$P = \varepsilon_0 \varepsilon_r E - \varepsilon_0 E$$

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

Electric Susceptibility (χ_e) : The polarization **P** is proportional to the total electronic flux density E and is in the same direction of E. Therefore, the polarization vector can be written as

$$P = \varepsilon_0 \chi_e E$$

$$\text{Therefore } \chi_e = P / \varepsilon_0 E = \varepsilon_0(\varepsilon_r - 1)E / \varepsilon_0 E$$

$$\chi_e = (\varepsilon_r - 1)$$

Dielectric Strength: It can be defined as the minimum voltage required for producing dielectric breakdown. Dielectric strength decreases with raising the temperature, humidity and age of the material.

Various polarization Process: polarization occurs due to several atomic mechanisms. When a specimen is placed in a d.c. electric field, polarization is due to four types of processes. They are

(1) electronic polarization
(2) ionic polarization
(3) orientation polarization and
(4) space charge polarization

✓ **Electronic Polarization:** the process of producing electric dipoles which are oriented along the field direction is called polarization in dielectrics

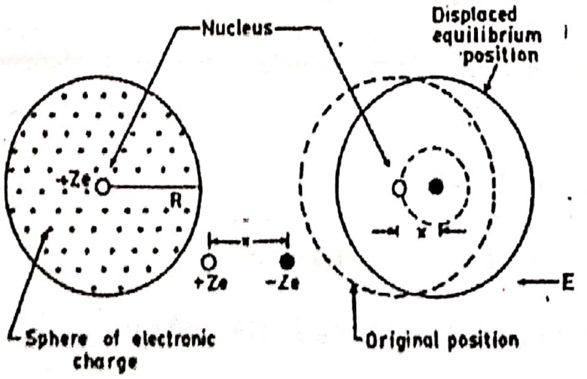
Consider an atom placed inside an electric field. The centre of positive charge is displaced along the applied field direction while the centre of negative charge is displaced in the opposite direction ,thus a dipole is produced.
The displacement of the positively charged nucleus and the negative electrons of an atom in opposite directions, on application of an electric field, result in electronic polarization.

Induced dipole moment

$\mu \propto E$ or $\mu = \alpha_e E$ where α_e is electronic polarizability

Electronic polarizability is independent of temperature.

Derivation: Consider the nucleus of charge Ze is surrounded by an electron cloud of charge -Ze distributed in a sphere of radius R.



Charge density ρ is given by

$$\rho = -Ze / ({}^4/_3 \Pi R^3) = -(3/4)(Ze / \Pi R^3) \text{ ----------(1)}$$

When an external field of intensity E is applied, the nucleus and electrons experiences Lorentz forces in opposite direction. Hence the nucleus and electron cloud are pulled apart.

Then Coulomb force develops between them, which tends to oppose the displacement. When Lorentz and coulomb forces are equal and opposite, equilibrium is reached.

Let x be the displacement

Lorentz force = $-ZeE$ (since = charge x applied field)

Coulomb force = $Ze \times$ [charge enclosed in sphere of radius 'x' / $4\Pi\varepsilon_0 x^2$]

$$\left[F = \frac{q_1 q_2}{4\pi\varepsilon_0 x^2}\right]$$

Charge enclosed $= (4/3)\Pi x^3 \rho$

$= (4/3)\Pi x^3 [(-3/4)(Ze / \Pi R^3)]$

$= -Zex^3 / R^3$

Therefore Coulomb force = $(Ze)(-Zex^3/R^3)/4\Pi\varepsilon_0 x^2 = -Z^2e^2x/4\Pi\varepsilon_0 R^3$

At equilibrium, Lorentz force = Coulomb force

$\therefore -ZeE = -Z^2e^2x/4\Pi\varepsilon_0 R^3$

⇨ $E = -Zex/4\Pi\varepsilon_0 R^3$

⇨ or $x = 4\Pi\varepsilon_0 R^3 E / Ze$

Thus displacement of electron cloud is proportional to applied field.

The two charges +Ze and -Ze are separated by a distance 'x' under applied field constituting induced electric dipoles .

Induced dipole moment $\mu_e = Zex$

Therefore $\mu_e = Ze(4\Pi\varepsilon_0 R^3 E/Ze) = 4\Pi\varepsilon_0 R^3 E$

Therefore $\mu_e \propto E$, $\mu_e = \alpha_e E$ where $\alpha_e = 4\Pi\varepsilon_0 R^3$ is electronic polarizability

The dipole moment per unit volume is called electronic polarization. It is independent of temperature.

$P = N\mu_e = N\alpha_e E$ where

N is Number of atoms / m^3

$P_e = N(4\Pi\varepsilon_0 R^3 E) = 4\Pi\varepsilon_0 R^3 NE$ where

R is radius of atom

④

Electric Susceptibility $\chi = P / \varepsilon_0 E$

Therefore $P = \varepsilon_0 E \chi$

$P = (4 \Pi R^3 N) \varepsilon_0 E$ where $\chi = 4 \Pi R^3 N$

Also $P_e = \varepsilon_0 E (\varepsilon_r - 1) = N \alpha_e E$

Or $\varepsilon_r - 1 = N \alpha_e / \varepsilon_0$

Hence $\alpha_e = \varepsilon_0 (\varepsilon_r - 1) / N$.

Ionic Polarization: It is due to the displacement of cat ions and anions in opposite directions and occurs in an ionic solid .

Consider a NaCl molecule. Suppose an electric field is applied in the positive direction . The positive ion moves by x_1 and the negative ion moves by x_2

Note

$F = kx \quad \left[k = \frac{F}{x} = \frac{ma}{x} = \frac{m\omega^2 \cancel{x}}{\cancel{x}}\right]$

$\Rightarrow Eq = kx$

$\Rightarrow Ee = m\omega^2 x$

$\Rightarrow \boxed{x = \frac{eE}{m\omega^2}}$

Let M is mass of positive ion

M is mass of negative ion

x_1 is displacement of positive ion

x_2 is displacement of negative ion

Total displacement $x = x_1 + x_2$ ----------(1)

Lorentz force on positive ion $= +eE$ ----------(2)

Lorentz force on negative ion $= -eE$ ----------(3)

Restoring force on positive ion $= -k_1 x_1$----------(2 a)

Restoring force on negative ion $= +k_2 x_2$----------(3 a) where k_1, k_2 Restoring force constants

At equilibrium, Lorentz force and restoring force are equal and opposite

$$\left.\begin{array}{l} \text{For positive ion, } eE = k_1 x_1 \\ \text{For negative ion, } eE = k_2 x2 \end{array}\right] \text{---------- (4)}$$

Where $k_1 = M \omega_0^2$ & $k_2 = m \omega_0^2$ where ω_0 is angular velocity of ions

Therefore $x = x_1 + x_2 = (eE / \omega_0^2)\ [1/M + 1/m]$------------(5)

From definition of dipole moment

μ = charge x distance of separation

$\mu = ex = (e^2 E / \omega_0^2)\ [1/M + 1/m]$ ------------(6)

But $\mu \, \alpha \, E$ or $\mu = \alpha_i E$

Therefore $\alpha_i = (e2 / \omega_0^2)\ [1/M + 1/m]$

This is ionic polarizability.

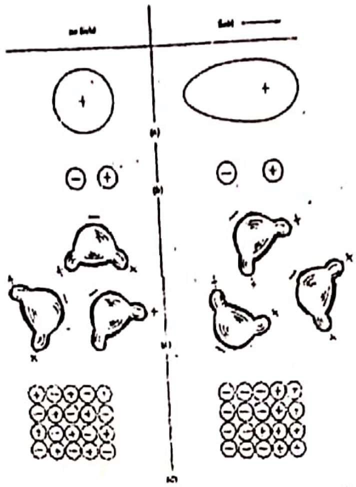


Fig. 5a. Various polarization processes (a) electronic polarization, (b) ionic pol (c) orientation polarization, and (d) space charge polarization.

Orientational Polarization:

In methane molecule, the centre of negative and positive charges coincides, so that there is no permanent dipole moment. On the other hand, in certain molecules such as Ch3Cl, the positive and negative charges do not coincide .Even in the absence of an electric field, this molecule carries a dipole moment, they tend to align themselves in the direction of applied field. The polarization due to such alignment is called orientation polarization. It is dependent on temperature. With increase of temperature the thermal energy tends to randomize the alignment.

Orientational polarization $P_o = N\mu = N\mu 2E / 3kT$

$$= N \alpha_0 E$$

Therefore Orientational polarizability $\alpha_0 = P_o / NE = \mu 2 / 3kT$

Thus orintational polarizability α_0 is inversely proportional t absolute temperature of material.

Internal field or Local field or Lorentz field: Internal field is the total electric field at atomic site.

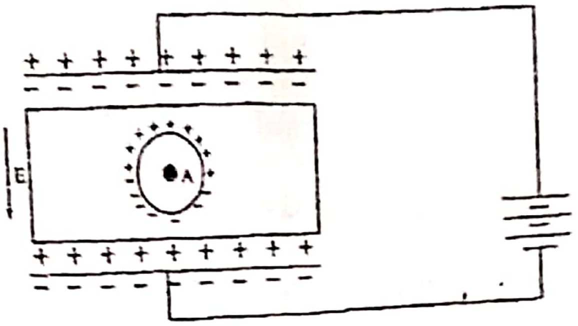
Internal field $A = E_1 + E_2 + E_3 + E_4$ ------ (I) where

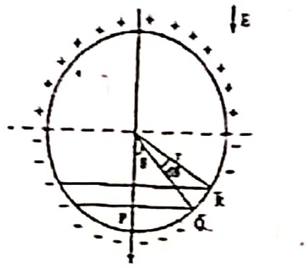
E_1 is field intensity due to charge density on plates

E_2 is charge density induced on two sides of dielectric

E_3 is field intensity due to other atoms in cavity and

E_4 is field intensity due to polarization charges on surface of cavity





Field E_1 : E_1 is field intensity due to charge density on plates

From the field theory

$$E_1 = D/\varepsilon_0$$

$$D = P + \varepsilon_0 E$$

Therefore $E_1 = P + \varepsilon_0 E / \varepsilon_0 = E + P/\varepsilon_0$ ————(1)

Field E_2 : E_2 is the field intensity at A due to charge density induced on two sides of dielectric

Therefore $E_2 = -P/\varepsilon_0$ ————(2)

Field E_3 : E_3 is field intensity at A due to other atoms contained in the cavity and for a cubic structure,

$E_3 = 0$ because of symmetry. ———— (3)

Field E_4: E_4 is field intensity due to polarization charges on surface of cavity and was calculated by Lorentz in the following way:

If dA is the surface area of the sphere of radius r lying between θ and θ + dθ, where θ is the direction with reference to the direction of applied force.

Then $dA = 2\Pi (PQ)(QR)$

But $\sin\theta = PQ/r \Rightarrow PQ = r\sin\theta$

And $d\theta = QR/r \Rightarrow QR = r\,d\theta$

Hence $dA = 2 \Pi (r \sin \theta)(r\, d\theta) = 2 \Pi r^2 \sin \theta\, d\theta$

Charge on surface dA is $dq = P \cos \theta\, dA$ (cos θ is normal component)

$$dq = P \cos \theta (2 \Pi r^2 \sin \theta\, d\theta) = P (2 \Pi r^2 \sin \theta \cos \theta\, d\theta)$$

The field due to the charge dq at A, is denoted by $dE_{4\,in}$ direction $\theta = 0$

$$dE_4 = dq \cos \theta / 4 \Pi \varepsilon_0 r^2 = P (2 \Pi r^2 \sin \theta \cos \theta\, d\theta) \cos \theta$$

$$dE_4 = P \sin \theta \cos^2 \theta\, d\theta / 2 \varepsilon_0$$

$$\int dE_4 = P / 2 \varepsilon_0 \int_0^{\Pi} \sin \theta \cos^2 \theta\, d\theta = P / 2 \varepsilon_0 \int_0^{\Pi} \cos^2 \theta\, d(-\cos \theta)$$

Let $\cos \theta = x$

$$\int dE_4 = - P / 2 \varepsilon_0 \int_0^{\Pi} x^2\, dx$$

Therefore $E_4 = - P / 2 \varepsilon_0 \, [x3 / 3]_0^{\Pi}$

$$= - P / 2 \varepsilon_0 \, [\cos 3\, \theta / 3]_0^{\Pi} = - P / 6 \varepsilon_0 \, [-1 - 1] = P / 3 \varepsilon_0 \quad \text{------- (4)}$$

Local field $E_i = E1 + E_2 + E_3 + E_4$

$$= E + P / \varepsilon_0 - P / \varepsilon_0 + 0 + P / 3 \varepsilon_0$$

$$= E + P / 3 \varepsilon_0$$

Clausius – Mosotti Relation:

Let us consider the elemental dielectric having cubic structure. Since there are no ions and perment dipoles in these materials, them ionic polarizability α_i and orientational polarizability α_0 are zero.

i.e. $\alpha_i = \alpha_0 = 0$

Hence polarization $P = N \alpha_e E_i$

$$= N \alpha_e (E + P / 3\varepsilon_0)$$

$$\text{i.e. } P [1 - N \alpha_e / 3 \varepsilon_0] = N \alpha_e E$$

$$P = N \alpha_e E / P [1 - N \alpha_e / 3 \varepsilon_0] \longrightarrow 1$$

$$D = P + \varepsilon_0 E$$

$$P = D - \varepsilon_0 E$$

Dividing on both sides by E

$$P / E = D / E - \varepsilon_0 = \varepsilon - \varepsilon_0 = \varepsilon_0 \varepsilon_r - \varepsilon_0$$

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

From eqn 1 and 2 , we get

$$P = E \varepsilon_0 (\varepsilon_r - 1) = N \alpha_e E / [1 - N \alpha_e / 3 \varepsilon_0]$$

$$[1 - N \alpha_e / 3 \varepsilon_0] = N \alpha_e / \varepsilon_0 (\varepsilon_r - 1)$$

$$1 = N \alpha_e / 3 \varepsilon_0 + N \alpha_e / \varepsilon_0 (\varepsilon_r - 1)$$

$$1 = (N \alpha_e / 3 \varepsilon_0) (1 + 3 / (\varepsilon_r - 1))$$

$$1 = (N \alpha_e / 3 \varepsilon_0)[(\varepsilon_r - 1 + 3) / (\varepsilon_r - 1)]$$

$$1 = (N \alpha_e / 3 \varepsilon_0)[(\varepsilon_r + 2) / (\varepsilon_r - 1)]$$

$(\varepsilon_r + 2) / (\varepsilon_r - 1) = N \alpha_e / 3 \varepsilon_0$ Where N – no of molecules per unit volume

This is Clausius – Mosotti Relation.

Dielectric Breakdown : The dielectric breakdown is the sudden change in state of a dielectric material subjected to a very high electric field , under the influence of which , the electrons are lifted into the conduction band causing a surge of current , and the ability of the material to resist the current flow suffers a breakdown .

Or

When a dielectric material loses its resistivity and permits very large current to flow through it, then the phenomenon is called dielectric breakdown.

There are many factors for dielectric breakdown which are (1) Intrinsic breakdown (2) Thermal breakdown (3) Discharge breakdown (4) Electro Chemical breakdown (5) Defect breakdown.

(1) **Intrinsic breakdown**: The dielectric strength is defined as the breakdown voltage per unit thickness of the material. When the applied electric field is large, some of the electrons in the valence band cross over to the conduction band across the large forbidden energy gap giving rise to large conduction currents. The liberation or movement of electrons from valence band is called field emission of electrons and the breakdown is called the intrinsic breakdown or zener breakdown.

The number of covalent bonds broken and the number of charge carriers released increases enormously with time and finally dielectric breakdown occurs. This type of breakdown is called Avalanche breakdown.

⑨

(2) **Thermal breakdown:** It occurs in a dielectric when the rate of heat generation is greater than the rate of dissipation. Energy due to the dielectric loss appears as heat. If the rate of generation of heat is larger than the heat dissipated to the surrounding, the temperature of the dielectric increases which eventually results in local melting .once melting starts, that particular region becomes highly conductive, enormous current flows through the material and dielectric breakdown occurs.

Thus thermal breakdown occurs at very high temperatures. Since the dielectric loss is directly proportional to the frequency, for a.c fields, breakdown occurs at relatively lower field strengths.

(3) **Discharge breakdown:** Discharge breakdown is classified as external or internal. External breakdown is generally caused by a glow or corona discharge .Such discharges are normally observed at sharp edges of electrodes. It causes deterioration of the adjacent dielectric medium. It is accompanied by the formation of carbon so that the damaged areas become conducting leading to power arc and complete failure of the dielectric. Dust or moisture on the surface of the dielectric may also cause external discharge breakdown. Internal breakdown occurs when the insulator contains blocked gas bubbles .If large number of gas bubbles is present, this can occur even at low voltages.

(4) **Electro Chemical breakdown:** Chemical and electro chemical breakdown are related to thermal breakdown. When temperature rises, mobility of ions increases and hence electrochemical reaction takes place. When ionic mobility increases leakage current also increases and this may lead to dielectric breakdown. Field induced chemical reaction gradually decreases the insulation resistance and finally results in breakdown.

(5) **Defect breakdown:** if the surface of the dielectric material has defects such as cracks and porosity, then impurities such as dust or moisture collect at these discontinuities leading to breakdown. Also if it has defect in the form of strain in the material, that region will also break on application of electric field.

Frequency dependence of polarizability:

On application of an electric field, polarization process occurs as a function of time. The polarization P(t) as a function of time. The polarization P(t) as a function of time t is given by

$$P(t) = P[\,1 - \exp(-t/t_r)]$$

Where P – max. Polarization attained on prolonged application of static field.

t_r - relaxation time for particular polarization process

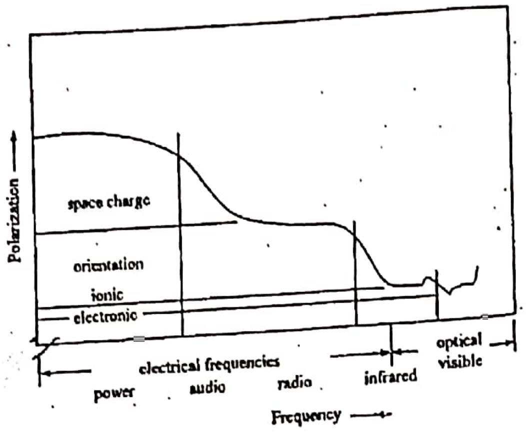
The relaxation time t_r is a measure of the time scale of polarization process. It is the time taken for a polarization process to reach 0.63 of the max. value.

Electronic polarization is extremely rapid. Even when the frequency of the applied voltage is very high in the optical range (~10^{15} Hz), electronic polarization occurs during every cycle of the applied voltage.

Ionic polarization is due to displacement of ions over a small distance due to the applied field. Since ions are heavier than electron cloud, the time taken for displacement is larger. The frequency with which ions are displaced is of the same order as the lattice vibration frequency (≈1013Hz). Hence, at optical frequencies, there is no ionic polarization. If the frequency of the applied voltage is less than 1013 Hz, the ions respond.

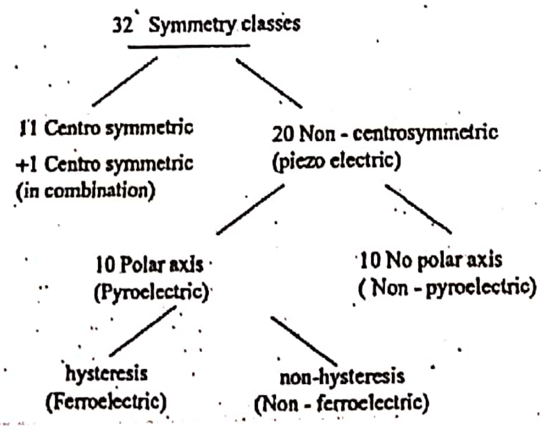
Orientation polarization is even slower than ionic polarization. The relaxation time for orientation polarization in a liquid is less than that in a solid. Orientation polarization occurs, when the frequency of applied voltage is in audio range (1010 Hz).

Space charge polarization is the slowest process, as it involves the diffusion of ions over several interatomic distances. The relaxation time for this process is related to frequency of ions under the influence of applied field. Space charge polarization occurs at power frequencies (50-60 Hz).



Piezo – Electricity: These materials have the property of becoming electrically polarized when mechanical stress is applied. This property is known as Piezo – electric effect has an inverse .According to inverse piezo electric effect, when an electric stress or voltage is applied, the material becomes strained. The strain is directly proportional to the applied field E.

When piezo electric crystals are subjected to compression or tension, opposite kinds of charges are developed at the opposite faces perpendicular to the direction of applied force. The charges produced are proportional to the applied force.



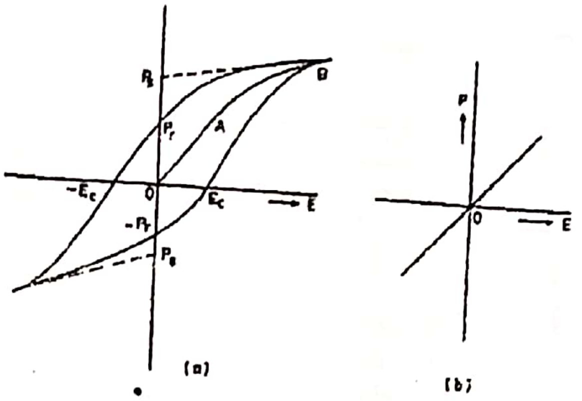
Piezo – Electric Materials and Their Applications: Single crystal of quartz is used for filter, resonator and delay line applications. Natural quartz is now being replaced by synthetic material.

Rochelle salt is used as transducer in gramophone pickups, ear phones, hearing aids, microphones etc. the commercial ceramic materials are based on barium titanate, lead zirconate and lead titanate. They are used for high voltage generation (gas lighters), accelerometers, transducers etc.

Piezo electric semiconductors such as GaS, ZnO & CdS are used as amplifiers of ultrasonic waves.

Ferro electricity: Ferro electric materials are an important group not only because of intrinsic Ferro electric property, but because many possess useful piezo electric, birefringent and electro optical properties.

The intrinsic Ferro electric property is the possibility of reversal or change of orientation of the polarization direction by an electric field. This leads to hysteresis in the polarization P, electric field E relation, similar to magnetic hysteresis. Above a critical temperature, the Curie point T_c, the spontaneous polarization is destroyed by thermal disorder. The permittivity shows a characteristic peak at T_c.



Pyroelectricity: It is the change in spontaneous polarization when the temperature of specimen is changed.

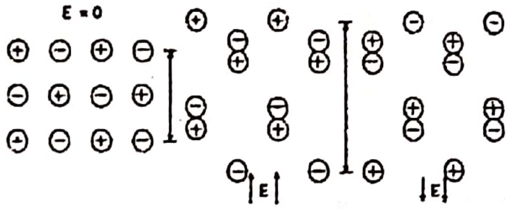


Fig Displacements of the ions under an electric field

Pyroelectric coefficient 'λ' is defined as the change in polarization per unit temperature change of specimen.

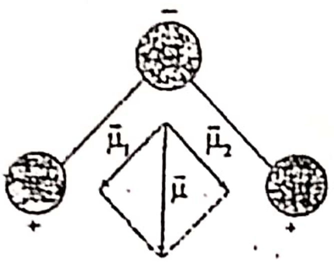
$$\lambda = dP / dT$$

change in polarization results in change in external field and also changes the surface.

Required Qualities of Good Insulating Materials: The required qualities can be classified as under electrical, mechanical, thermal and chemical applications.

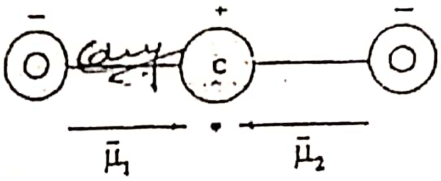
Difference between polar and non polar dielectrics:-

Polar dielectrics	Non polar dielectrics
1. They have permanent dipole moments even in the absence of an applied field.	1. They do not have permanent dipole moments. But they have induced dipole moments in the presence of an applied field
2. There is absorption or emission in infrared range for the molecules of polar dielectrics.	2. There is no absorbtioOn or emission in Infrared range for the molecules of on polar dielectrics.
3. The polarisation of polar molecule strongly temperature dependent.	3. The polarisation of non polar molecules is independent of temperature.
4. They do not have centre of symmetry.	4. They have centre of symmetry.
5. Examples Hcl, H_2O, CO.	5. Examples O_2, H_2, N_2.



$\bar{\mu} = \bar{\mu}_1 - \bar{\mu}_2$

(b) Polar dielectric



$\bar{\mu} = \bar{\mu}_1 - \bar{\mu}_2 = 0$

(a) Non-polar dielectric

Dielectric constant(ε_r)

The dielectric characteristics of a material are determined by the dielectric constant or relative permittivity ε_r of that material. *Dielectric constant is the ratio between the permittivity of the medium and the permittivity of free space.*

$$\text{i.e.} \quad \varepsilon_r = \frac{\varepsilon}{\varepsilon_o} \qquad (1)$$

Since it is a ratio of same quantity, ε_r has no unit. It is a measure of polarization in the dielectric material.

[illegible]. MAGNETIC PROPERTIES

Introduction : The basic aim in the study of the subject of magnetic materials is to understand the effect of an external magnetic field on a bulk material ,and also to account for its specific behavior. A dipole is an object that a magnetic pole is on one end and a equal and opposite second magnetic dipole is on the other end.

A bar magnet can be considered as a dipole with a north pole at one end and South Pole at the other. If a magnet is cut into two, two magnets or dipoles are created out of one. This sectioning and creation of dipoles can continue to the atomic level. Therefore, the source of magnetism lies in the basic building block of all the matter i.e. the atom.

Consider electric current flowing through a conductor. When the electrons are flowing through the conductor, a magnetic field is forms around the conductor. A magnetic field is produced whenever an electric charge is in motion. The strength of the field is called the **magnetic moment.**

Magnetic materials are those which can be easily magnetized as they have permanent magnetic moment in the presence of applied magnetic field. Magnetism arises from the magnetic dipole moments. It is responsible for producing magnetic influence of attraction or repulsion.

Magnetic dipole : it is a system consisting of two equal and opposite magnetic poles separated by a small distance of '2l'metre.

✓ ***Magnetic Moment*** ($\overset{M}{\mu_m}$) **:**It is defined as the product of the pole strength (m) and the distance between the two poles (2l) of the magnet.

$$\text{i.e.}\;\; \overset{M}{\cancel{\mu_m}} = (2l)\,m$$

Units: Ampere – metre^2

✓ ***Magnetic Flux Density or Magnetic Induction (B):*** It is defined as the number of magnetic lines of force passing perpendicularly through unit area.

$$\text{i.e.}\;\; \mathbf{B} = \text{magnetic flux / area} = \Phi / A$$

Units: Weber / metre^2 or Tesla.

✓ ***Permeability:*** (μ) The ability of the medium which allows magnetic lines of force

✓ ***Magnetic Field Intensity (H):*** The magnetic field intensity at any point in the magnetic field is the force experienced by a unit north pole placed at that point.

Units: Ampere / meter

The magnetic induction B due to magnetic field intensity H applied in vacuum is related by

$\mathbf{B} = \mu_0 \mathbf{H}$ where μ_0 is permeability of free space $= 4\Pi \times 10^{-7}$ H / m

If the field is applied in a medium, the magnetic induction in the solid is given by

$\mathbf{B} = \mu \mathbf{H}$ where μ is permeability of the material in the medium

$\mu = B / H$

Hence magnetic Permeability μ of any material is the ratio of the magnetic induction to the applied magnetic field intensity. The ratio of μ / μ_0 is called the relative permeability (μ_r).

$\mu_r = \mu / \mu_0$

Therefore $\mathbf{B} = \mu_0 \mu_r \mathbf{H}$

Magnetization: It is the process of converting a non – magnetic material into a magnetic material. The intensity of magnetization (M) of a material is the magnetic moment per unit volume. The intensity of magnetization is directly related to the applied field H through the susceptibility of the medium (χ) by

$\chi = M / H$ ------------(1)

(χ) The magnetic susceptibility of a material is the ratio of the intensity of magnetization produced to the magnetic field intensity which produces the magnetization. It has no units. $(\chi) = \frac{M}{H}$

~~We know~~ Relation between B, H and M

we know $\mathbf{B} = \mu \mathbf{H}$

$= \mu_0 \mu_r \mathbf{H}$

i.e $\mathbf{B} = \mu_0 \mu_r \mathbf{H} + \mu_0 \mathbf{H} - \mu_0 \mathbf{H}$

$= \mu_0 \mathbf{H} + \mu_0 \mathbf{H} (\mu_r - 1)$

$= \mu_0 \mathbf{H} + \mu_0 \mathbf{M}$ where M is magnetization $= \mathbf{H} (\mu_r - 1)$

i.e $\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M})$ ----------(2)

The first term on the right side of eqn (2) is due to external field. The second term is due to the magnetization.

Hence $\mu_0 = \mathbf{B} / \mathbf{H} + \mathbf{M}$

Relative Permeability (μ_r) :-

$\mu_r = \mu / \mu_0 - (\mathbf{B}/\mathbf{H}) / (\mathbf{B}/\mathbf{H} + \mathbf{M}) = \mathbf{H} + \mathbf{M}/\mathbf{H} = 1 + \mathbf{M}/\mathbf{H}$

$\mu_r = 1 + \chi$ --------(3)

②

The magnetic properties of all substances are associated with the orbital and spin motions of the electrons in their atoms. Due to this motion, the electrons become elementary magnets of the substance. In few materials these elementary magnets are able to strengthen the applied magnetic field , while in few others , they orient themselves such that the applied magnetic field is weakened.

Origin of Magnetic Moment : In atoms , the permanent magnetic moments can arise due to the following :

1. the orbital magnetic moment of the electrons
2. the spin magnetic moment of the electrons
3. the spin magnetic moment of the nucleus.

① *Orbital magnetic moment of the electrons:* In an atom, electrons revolve round the nucleus in different circular orbits.

Let m be the mass of the electron and r be the radius of the orbit in which it moves with angular velocity ω.

The electric current due to the moving electron I = - (number of electrons flowing per second x charge of an electron)

Therefore $I = -e\omega / 2\Pi$ --------------(1)

The current flowing through a circular coil produces a magnetic field in a direction perpendicular to the area of coil and it is identical to the magnetic dipole. the magnitude of the magnetic moment produced by such a dipole is

$$\mu_m = I.A$$

$$= (-e\omega/2\Pi)(\Pi r^2)$$

$$= -e\omega r^2/2 = (-e/2m)(m\omega r^2) = -(e/2m)L \text{ ----------(2)}$$

where $L = m\omega r^2$ is the orbital angular momentum of electron. The minus sign indicates that the magnetic moment is anti – parallel to the angular momentum L. A substance therefore possesses permanent magnetic dipoles if the electrons of its constituent atom have a net non-vanishing angular momentum. The ratio of the magnetic dipole moment of the electron due to its orbital motion and the angular momentum of the orbital motion is called orbital gyro magnetic ratio , represented by γ.

Therefore γ = magnetic moment / angular momentum = e / 2m

The angular momentum of an electron is determined by the orbital quantum number 'l' given by $l = 0, 1, 2, \ldots\ldots (n-1)$ where n is principal quantum number $n = 1, 2, 3, 4, \ldots\ldots$ ……corresponding to K , L , M , N……shells .
The angular momentum of the electrons associated with a particular value of l is given by $l(h/2\Pi)$

The strength of the permanent magnetic dipole is given by

$$\mu_{el} = -(e/2m)(lh/2\Pi)$$

i.e $\mu_{el} = -(e h l / 4 \Pi m) = -\mu_B l$ --------------(3)

The quantity $\mu_B = e h / 4 \Pi m$ is an atomic unit called Bohr Magneton and has a value 9.27×10^{-24} ampere metre^2

In an atom having many electrons, the total orbital magnetic moment is determined by taking the algebraic sum of the magnetic moments of individual electrons. The moment of a completely filled shell is zero. An atom with partially filled shells will have non zero orbital magnetic moment.

② *Magnetic Moment Due to Electron Spin.:* The magnetic moment associated with spinning of the electron is called spin magnetic moment μ_{es} .Magnetic moment due to the rotation of the electronic charge about one of the diameters of the electron is similar to the earth's spinning-motion around it's north – south axis.

An electronic charge being spread over a spherical volume ,the electron spin would cause different charge elements of this sphere to form closed currents, resulting in a net spin magnetic moment. This net magnetic moment would depend upon the structure of the electron and its charge distribution.

$\mu_{es} = \gamma (e / 2 m) S$ -------------------(1)where $S = h / 4 \Pi$ is spin angular momentum

therefore $\mu_{es} \approx 9.4 \times 10^{-24}$ .ampere metre^2

Thus, the magnetic moments due to the spin and the orbital motions of an electron are of the same order of magnitude. The spin and electron spin magnetic moment are intrinsic properties of an electron and exist even for a stationary electron. Since the magnitude of spin magnetic moment is always same, the external field can only influence its direction. If the electron spin moments are free to orient themselves in the direction of the applied field B In a varying field ,it experiences a force in the direction of the increasing magnetic field due to spin magnetic moments of its various electrons.

③ *Magnetic Moment due to Nuclear Spin :* Another contribution may arise from the nuclear magnetic moment. By analogy with Bohr Magneton, the nuclear magneton arises due to spin of the nucleus. It is given by

$$\mu_{ps} = e h / 4 \Pi M_p$$

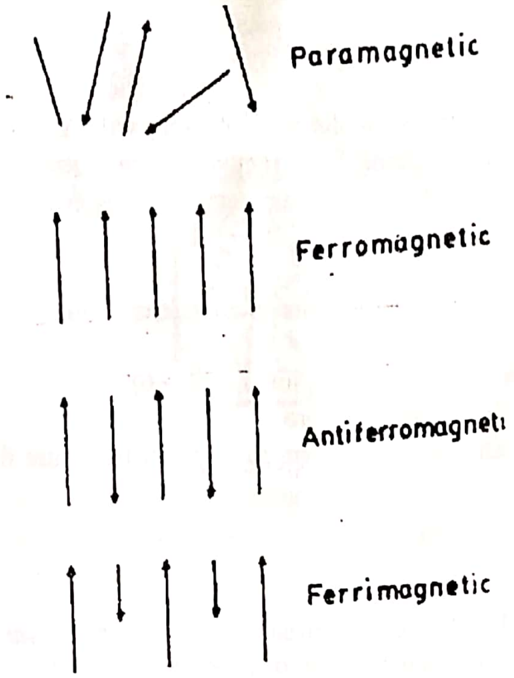
$$\mu_{ps} = 5.05 \times 10^{-27} \text{ ampere metre}^2 \quad \text{where } M_p \text{ is mass of proton.}$$

The nuclear magnetic moments are smaller than those associated with electrons.

✓ ***Classification Of Magnetic Materials :*** All matter respond in one way or the other when subjected to the influence of a magnetic field. The response could be strong or weak, but there is none with zero response ie, there is no matter which is non magnetic in the absolute sense. Depending upon the magnitude and sign of response to the applied field , and also on the basis of effect of temperature on the magnetic properties, all materials are classified broadly under 3 categories.

1. Diamagnetic materials 2. Paramagnetic materials, 3. Ferromagnetic materials

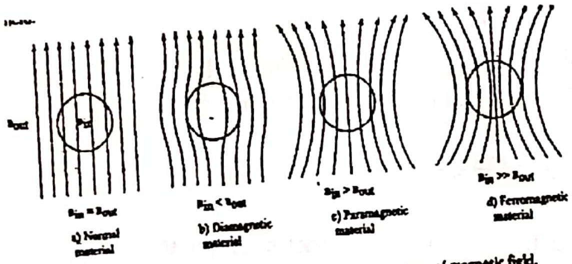
two more classes of materials have structure very close to ferromagnetic materials but possess quite different magnetic effects. They are i. Anti ferromagnetic materials and ii. Ferri magnetic materials



1. ***Diamagnetic materials: Diamagnetic*** materials are those which experience a repelling force when brought near the pole of a strong magnet. In a non uniform magnetic field they are repelled away from stronger parts of the field.

In the absence of an external magnetic field, the net magnetic dipole moment over each atom or molecule of a diamagnetic material is zero.

Ex: Cu, Bi, Pb .Zn and rare gases.



a) Normal material
b) Diamagnetic material
c) Paramagnetic material
d) Ferromagnetic material

Fig. — The behaviour of magnetic materials in the presence of magnetic field.

2, **Paramagnetic materials:** Paramagnetic materials are those which experience a feeble attractive force when brought near the pole of a magnet. They are attracted towards the stronger parts of magnetic field. Due to the spin and orbital motion of the electrons, the atoms of paramagnetic material posses a net intrinsic permanent moment.

Susceptibility χ is positive and small for these materials. The susceptibility is inversely proportional to the temperature T.

$\chi \alpha 1/T$

$\chi = C/T$ where C is Curie's temperature.

Below superconducting transition temperatures, these materials exhibit the Para magnetism.

Examples: Al, Mn, Pt, $CuCl_2$.

3. **Ferromagnetic Materials:** Ferromagnetic materials are those which experience a very strong attractive force when brought near the pole of a magnet. These materials, apart from getting magnetized parallel to the direction of the applied field, will continue to retain the magnetic property even after the magnetizing field removed. The atoms of ferromagnetic materials also have a net intrinsic magnetic dipole moment which is due to the spin of the electrons.

Susceptibility is always positive and large and it depends upon temperature.

$\chi = C / (T - \theta)$ (only in paramagnetic region i.e., $T > \theta$)

θ is Curie's temperature.

When the temperature of the material is greater than its Curie temperature then it converts into paramagnetic material.

Examples: Fe, Ni, Co, MnO.

Antiferromagnetic matériels : These are the ferromagnetic materials in which equal no of opposite spins with same magnitude such that the orientation of neighbouring spins is in antiparallel manner are present.

Susceptibility is small and positive and it is inversely proportional to the temperature.

$\chi = C / (T + \theta)$

the temperature at which anti ferromagnetic material converts into paramagnetic material is known as Neel's temperature.

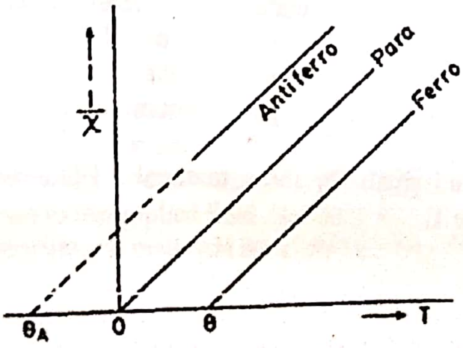
Examples: FeO, Cr_2O_3.

Ferrimagnetic materials: These are the ferromagnetic materials in which equal no of opposite spins with different magnitudes such that the orientation of neighbouring spins is in antiparallel manner are present.

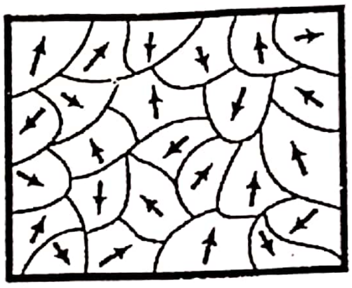
Susceptibility positive and large, it is inversely proportional to temperature

$\chi = C / (T \pm \theta)$ $T > T_N$ (Neel's temperature)

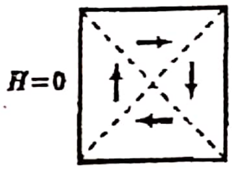
Examples : $ZnFe_2O_4$, $CuFe_2O_4$



Domain theory of ferromagnetism: According to Weiss, a virgin specimen of ferromagnetic material consists of a no of regions or domains (≈ 10-6 m or larger) 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. When an external field is applied there are two possible ways of alignment fo a random domain.

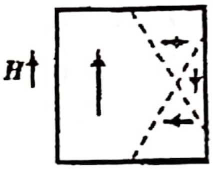


RANDOM ORIENTATION OF MAGNETIC MOMENTS OF THE DOMAINS



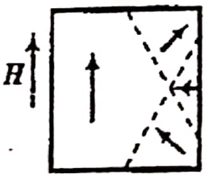
DOMAIN ORIENTATION IN THE ABSENCE OF MAGNETIC FIELD

(a)



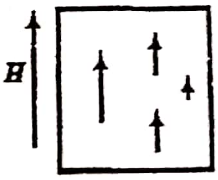
DOMAIN EMLARGEMENT / SRINKAGE DUE TO WEAK FIELDS

(b)



DOMAIN ROTATION DUE TO STRONG FIELDS

(c)



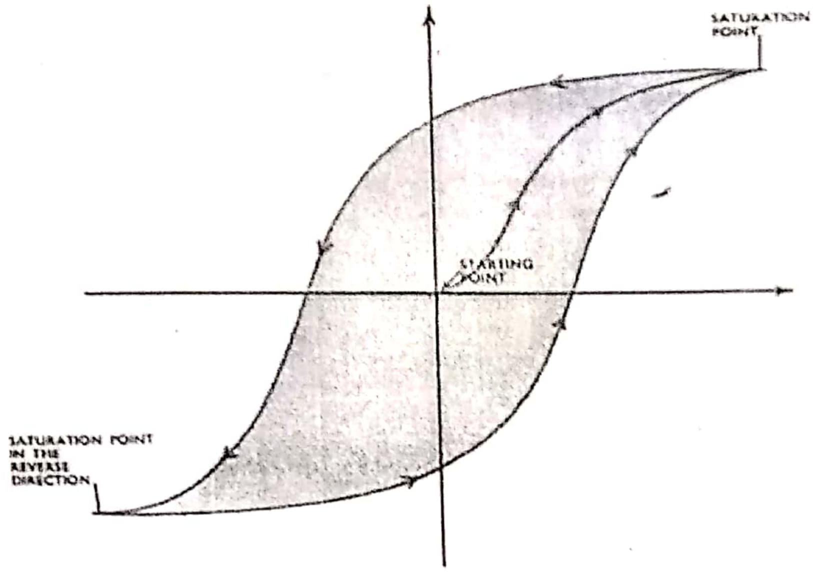
SATURATION DUE TO VERY HIGH FIELDS

(d)

i). **By motion of domain walls:** The volume of the domains that are favourably oriented with respect to the magnetizing field increases at the cost of those that are unfavourably oriented

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.

HYSTERISIS CURVE: (B -H : curve)



⑧

The hystereses of ferromagnetic materials represent the phenomenon of lagging of magnetization behind the applied magnetic field. It is an irreversible characteristic of ferromagnetic materials. The loop also reformed to hysteresis loop which is shown in fig.

1. When a magnetic field is applied on a ferromagnetic material the magnetization increases rapidly with applied field up to a value. after that it remains costant.this magnetization is known as "saturated intensity of magnetization"
2. If magnetic field on the material is reduced back to zero, magnetization will not travel in the initial path, it creates a new path and reaches to [illegible] called as "residual magnetization" and that point is called "retentivity"
3. If residual magnetization reduces to zero, -ve field has to be applied, when sufficient '-ve' field is applied the residual magnetization becomes zero and the field is known as "–ve cohecevive field".
4. If the –ve magnetic field is further applied then it increases the magnetization in –ve direction is called –ve saturated magnetization.
5. If the –ve field is decreases back to zero.the –ve saturated magnetization will not travel in the initial path,creats a new path and reaches to a point called '-ve'retentivity and the magnetization is called –ve residual magnetization.
6. In order to decreases the –ve residual magnetization to zero, some +ve field has to be applied. The amount of magnetic field required to bring residual magnetization to zero is known as cohersive field.
7. Further, the increases of +ve field the magnetization again reaches to +ve satururation.it is a cyclic process.
8. From this it is observed that the magnetization which is started from origin will not reach back to that point. Hence it is an irreversible process.

HYSTERISIS LOSS:

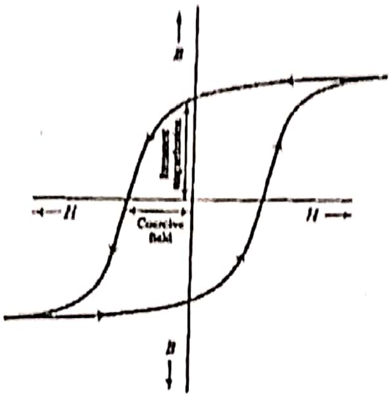
Hysteresis loss is the loss of energy in taking a Ferro magnetic material through a complete cycle of magnetization and this loss is repeated by the area enclosed by the hysteresis loop.

Hard and soft magnetic materials

Hysteresis loop of the ferromagnetic materials vary in size and shape. This variation in hysteresis loops leads to a broad classification of all the magnetic materials into hard type and soft type.

Hard Magnetic Materials:

Hard magnetic materials are those which are characterized by large hysteresis loop because of which they retain a considerable amount of their magnetic energy after the external magnetic field is switched off. These materials are subjected to a magnetic field of increasing intensity, the domain walls movements are impeded due to certain factors. The cause for such a nature is attributed to the presence of impurities or non-magnetic materials, or the lattice imperfections. Such defects attract the domain walls thereby reducing the wall energy. It results in a stable state for the domain walls and gives mechanical hardness to the material which increases the electrical resistivity. The increase in electrical resisitivity brings down the eddy current loss if used in a.c conditions. The hard magnetic materials can neither be easily magnetized nor easily demagnetized.



HYSTERESIS CURVE FOR HARD MAGNETIC MATERIAL

Properties:

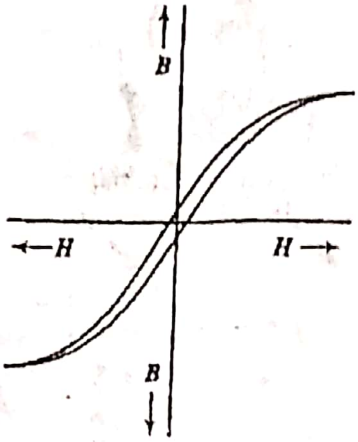
1. High remanent magnetization
2. High coercivity
3. High saturation flux density
4. Low initial permeability
5. High hysteresis energy loss
6. High permeability
7. The eddy current loss is low for ceramic type and large for metallic type.

Examples of hard magnetic materials are, i) Iron- nickel- aluminum alloys with certain amount of cobalt called Alnico alloy. ii) Copper nickel iron alloys. iii) Platinum cobalt alloy.

Applications of hard magnetic materials: For production of permanent magnets, used in magnetic detectors, microphones, flux meters, voltage regulators, damping devices and magnetic separators.

Soft Magnetic Materials:

Soft magnetic materials are those for which the hysteresis loops enclose very small area. They are the magnetic materials which cannot be permanently magnetized. In these materials ,the domain walls motion occurs easily. Consequently, the coercive force assumes a small value and makes the hysteresis loop a narrow one because of which, the hysteresis loss becomes very small. For the sane reasons, the materials can be easily magnetized and demagnetized.



HYSTERESIS CURVE FOR SOFT MAGNETIC MATERIAL

✓ *Properties:*

1. Low remanent magnetization
2. Low coercivity
3. Low hysteresis energy loss
4. Low eddy current loss
5. High permeability
6. High susceptibility

Examples of soft magnetic materials are

i) Permalloys (alloys of Fe and Ni)
ii) Si – Fe alloy
iii) Amorphous ferrous alloys (alloys of Fe, Si, and B)
iv) Pure Iron (BCC structure)

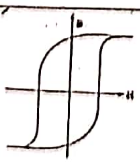
Applications of soft magnetic materials: Mainly used in electro- magnetic machinery and transformer cores. They are also used in switching circuits, microwave isolators and matrix storage of computers.

→ Flux (ϕ) :- The no. of magnetic lines of forces passing through normal to the Area of the magnet is called flux

Units :- weber

DISTINGUISH BETWEEN HARD AND SOFT MAGNETIC MATERIALS

Based on the shape of the hysteresis loop the magnetic materials are classified into hard and soft materials.

Hard magnetic materials	Soft magnetic materials
 The above fig shows the nature of the hysteresis loop of hard magnetic materials	 The above fig shows the nature of the hysteresis loop of soft magnetic materials.
1. These can not be easily magnetized and demagnetized.	1.These are easily magnetized and demagnetized
2. These materials have large hysteresis loss	2. They have very small hysteresis loss.
3. They have small permeability and susceptibility values.	3. They have high permeability and susceptibility values.
4. In these materials domain wall movement is difficult	4.The domain wall movement is easy
5. Coercivity and retentivity are very large.	5.The coercive and retentivity values are small
6. These have imperfections	6. These are free from imperfections.
7. They are used in permanent magnets	7.They are used in electromagnets
Eg. AlNiCO	eg.Fe-silicon alloys