Magnetic properties

Introduction: Magnetic materials play an important role in Industrial & scientific research fields. Based on the response of materials in the external field, they are classified into 3 categories: Dia, para & ferromagnetic which are further classified into 5 important groups depending on the alignment of magnetic moments within the material, Thus they are known as.

1. Diamagnetic, 2. Paramagnetic 3 Ferromagnetic
4. Antiferromagnetic 5. Ferrimagnetic

Basic Definitions:

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

Bohr Magneton: The magnetic movement contributed by an e^- with Angular momentum $n=1$ is known as Bohr magneton.

$$\mu_B = \frac{e\hbar}{2m} = 9.27 \times 10^{-24}$$

Magnetic susceptibility: It is defined as the intensity of magnetization produced in the substance per unit magnetic field strength

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

Magnetic permeability: measures degree to which the magnetic field can penetrate through the substance.

$$\mu_{\text{medium}} = \frac{B}{H} \qquad \mu_{0\,\text{free space}} = \frac{B_0}{H}$$

Relative permeability (μ_r):- $\mu_r = \frac{\mu}{\mu_0}$, $M = H(\mu_r - 1)$

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

Magnetic dipole moment: $M = IA$

magnetic field strength (H):- The force experienced by a unit North pole at any pt in the field is called magnetic field strength.

Magnetic Induction field strength & Magnetic flux density (B):- The no of magnetic lines of force passing through the unit area of cross section is called magnetic flux density

$$B = \frac{\phi}{A}$$

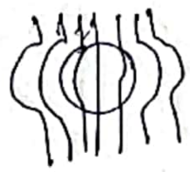
classification of magnetic materials

The different types of magnetic materials are:

(1) Diamagnetic materials: these substances which when placed in magnetic field acquire weak magnetism opposite to the direction of the field known as diamagnetic materials

Properties

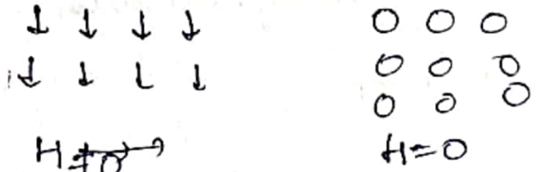
1. these materials are repelled by the magnets
2. when the diamagnetic materials is suspended in a uniform magnetic field (H) they set their longest axis at right Les to field
3. In a non-uniform H, these substances move from stronger parts of the field to weaker parts
4. $B_{in} < B_{out}$



5. χ is -ve , $\chi = \frac{M}{H} = -1$
6. χ is independent of Temp.
7. $\mu_r < 1$
8. Diamagnetic donot have permanent dipoles

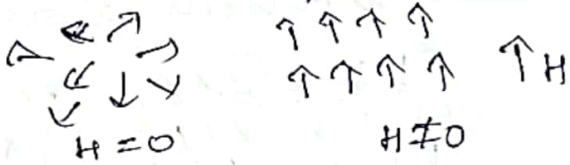
9. In an external field H. the orbital motion of e⁻s undergoes changes & the atoms acquire induced magnetic field is opp to field.

The induced dipoles & magnetization vanishes as soon as field is removed.



ex: Bismuth, cu, gold, quartz, water, Alcohol, mercury

Paramagnetic materials: acquire weak magnetism in the direction of the field.



properties:

1. paramagnetic materials have permanent dipoles
2. the dipoles are randomly oriented. Therefore the net magnetic moment is zero. In the presence of H dipoles are tending to allign in the direction of the field.
3. χ is +ve & $\chi \propto \frac{1}{T}$

   $\chi = \frac{C}{T} > 1$

   C → curie's const
4. $B_{in} > B_{out}$, paramagnetic materials are attracted by magnets
5. $\mu_r > 1$ ex: Aluminium, platinum, Cr, Mn, $CuSO_4$, O etc

Ferromagnetic materials: substances which when placed in H: become strongly magnetized in the direction of the field is known as ferromagnetic

properties

1. strongly attracted by magnets
2. $B_{in} >> B_{out}$, $\mu_r >> 1$

3. materials have permanent dipoles.

4. Dipoles are ||el to each other within the domains

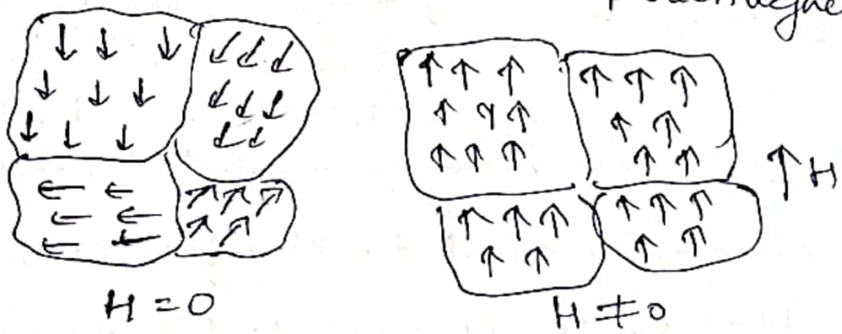
5. The net magnetic moment is zero due to Intermolecular field

6. The spin magnetic moments of unpaired $\bar{e}^s$ are responsible for it. They have spontaneous magnetisation

7. χ is very large depends on Temp.

$$\chi = \frac{C}{T-\theta} \gg 1$$

When Temp increases its χ decreases & shows paramagnetic behaviour above the paramagnetic curie Temp θ.



ex: Iron, cobalt, nickel & no of alloys

Ferrimagnetic materials: The materials which consist of Anti parallel magnetic moments of different magnitude.

$\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow$

Properties: 1. strongly attracted by magnets

2. $B_{in} \gg B_{out}$ $\mu_r \gg 1$

3. possess permanent dipoles

4. χ is very high & +ve for ferrimagnetic materials

5. $\chi = \frac{C}{T \pm \theta}$

ex: $PbFe_{12}O_{19}$, phyrrhotite $Fe_{1-x}S$.

Iron oxides with other elements as Al, Co, Ni

Antiferromagnetic materials: which consists of Anti parallel magnetic moments of equal magnitude

↑↓↑↓↑↓↑↓

Properties: 1. These are attracted by magnets

2. $B_{in} > B_{out}$ in Non uniform H, substances move from weaker parts to stronger parts

3. $\chi = \frac{C}{T+\theta}$, $\mu_r > 1$. to very small

ex Alloys of Iron & Mn, NiO.

Ferromagnetic domain theory

It states that ferromagnetic material consist of large no of small regions of spontaneous magnetisation called domains

• within each domain, the magnetic moments are aligned parallel to one another

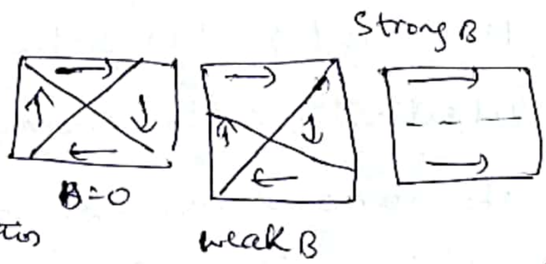
→ the direction of magnetisation varies from domain to domain & thus M is zero when H=0

→ when we apply an increasing H. initially the areas of the domains which are parallel to field are increased. In the final saturation stage, the other domains are rotated parallel to field.

→ the region of domain space is very small of order

Process of magnetisation:

1. By motion of domain walls:

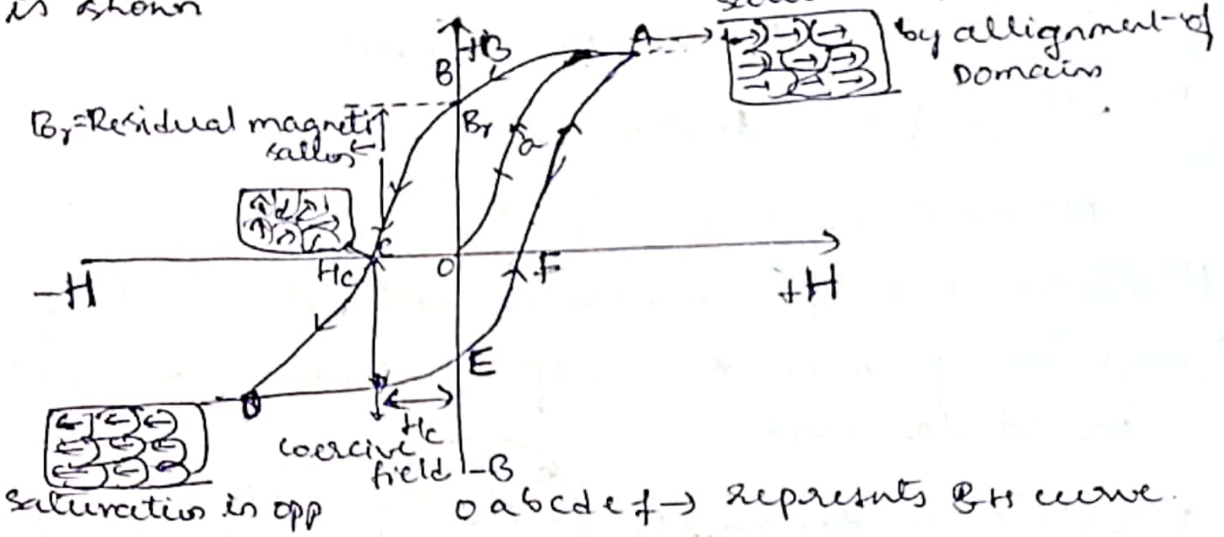


when small magnetic field is applied the domains of magnetisation either ∥el or nearby ∥el to field grow at the expense of others

By Rotation of domain :- Domains rotates in the field dirn.

Hysteresis on the basis of Domain theory

Lagging of B behind H is called Hysteresis.
When the specimen ferromagnetic material is placed in magnetic field. the variation of B with variation of H is shown



oabcdef → represents BH curve.

oa → due to smaller reversible domain wall movement

OB → due to small irreversible domain rotation.

When a field of small value H is applied, the domain walls are displaced & give rise to small magnetisation (oa) in graph.

At A all the domains alligned in the direction of H. no further enhancement is possible, therefore it attains saturation state.

Next, we decrease H & reduce it to zero. when H=0, B≠0. this represents the curve AB. is called Retentivity or Remenance. Br (Residual magnetism) The domains are not completely randomized even though the external driving field has been Removed

These domains are called irreversible domains.
This is due to small irreversible domain rotation.

Next, the ~~current~~ H in the solenoid is reversed & slowly increased. (This High reverse magnetic field can destroy the Retentivity). certain domains are flipped until the net field inside stands nullified. This represents the curve BC. The value of H at C is called coercivity. H_c

As the reversed H is increased in magnitude, we once again obtain saturation. The curve CD shows saturation.

Next H is reduced (curve DE) & reversed represents curve EF. It forms a cycle ABCDEF.

Thus the Reversible & irreversible domain wall movements give rise to hysteresis in ferromagnetic materials.

NOTE! the curve Oa. does not trace itself as H is reduced. For a given value of H, B is not unique it depends on previous history of the sample. This phenomenon is called Hysteresis

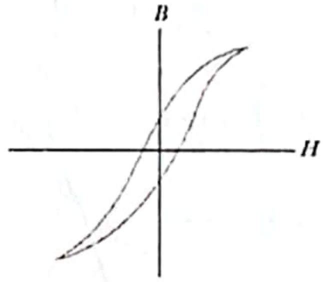
Hysteresis Loss! when a ferromagnetic material is subjected to cycles of magnetisation, the domains of the material resist being turned first in one direction & then in the other direction. Energy is expended in the material to overcome this opposition; this loss in the form of heat is called Hysteresis loss, effect is rise in Temp

5. Hard and soft magnetic materials

Based on the area of hysteresis, ferro magnetic materials can be classified into soft and hard magnetic materials.

Soft magnetic materials

The magnetized materials which are easily magnetized and demagnetized are known as soft magnetic materials.



Properties:

Soft magnetic materials have small hysteresis loop area.

Soft magnetic materials have low hysteresis loss.

Soft magnetic materials have small retentivity values.

Soft magnetic materials have small coercivity values

Soft magnetic materials require low magnetic field for magnetization.

Soft magnetic materials have high values of susceptibility and permeability.

Examples:- Iron-silicon alloys, Nickel-iron alloys, Iron-cobalt alloys.

Applications:

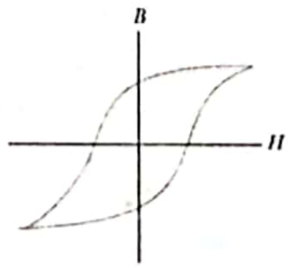
They are used in electrical equipments and magnetic cores and transformers.

They are used in motors, relays and sensors.

They are used in microwave isolators.

Hard magnetic materials

The magnetized materials which are hard to magnetize and demagnetize are known as hard magnetic materials.



Properties:

Hard magnetic materials have large hysteresis loop area.

Hard magnetic materials have large hysteresis loss.

Hard magnetic materials have large retentivity values

Hard magnetic materials have large coercivity values

Hard magnetic materials require large magnetic field for magnetization

Hard magnetic materials have low values of susceptibility and permeability

Examples:- carbon steel, tungsten steel, chromium steel.

Applications:

They are used into make permanent magnets.

They are used in dc meters and measuring devices.

They are used in speedometers and sensors in auto mobiles.

Dielectrics

Defn:

Dielectrics are non-conducting materials when kept in external field, they modify the electric field & themselves undergo some changes & start acting as stores of electric charges, such materials are dielectrics

electrons are tightly bound to the nuclei of atoms as these are Insulators. They have no (or negligible no of) charge carriers. However, when an external electric field is applied Induced charges appear on the surface of the dielectric. The Induced charges reduce the external electric field. The extent of effect depends on the nature of the dielectric. Dielectrics are so called because they can transmit electric field without actually conducting electricity.

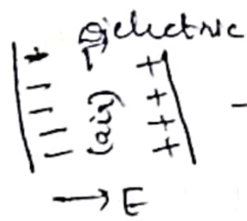
Eg: glass, polymers, ceramics etc

1) Dielectric material have dielectric constant.

$$K = \varepsilon_r = \frac{\varepsilon}{\varepsilon_0} = \frac{C}{C_0}$$

C → Presence of dielectric

C_0 → Absence of dielectric

2) 

→ capacitor is capable of storing charge hence electric energy, consists of two conducting surfaces seperated by an Insulating material.

3) (K) dielectric const is Independent of size & shape of dielectric material

4). capacitance (ability of capacitor to store charges) depends on the presence of dielectrics

presence of dielectric $C = \frac{\varepsilon_0 \varepsilon_r A}{d}$ In Absence of dielectric $C_0 = \frac{\varepsilon_0 A}{d}$

or $C = \frac{\varepsilon_0 K A}{d}$

5). Electric dipole. $(+q) \xleftrightarrow{x} (-q)$

dipole moment $\mu = q \cdot x$

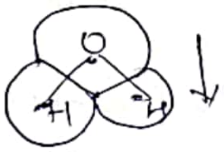
there are two types of dielectrics.

a) polar b) Non-polar.

a) Polar Dielectric: centres of +ve charge & the negative charge of each molecule donot coincide ∴ molecules of polar dielectrics have permanent dipole moments such dielectrics are called polar dielectrics.

molecules like NH_3, HCl ~~etc~~ water, alcohol etc have assymetric in shape. Due to finite seperation b/w ⊕ve & ⊖ve charge centre, each molecule behave as electric dipole.

HCl



H_2O.

ε_r varies from 3-8.

even though these have permanent dipole moment due to random orientation net dipole moment decreases.

b). Non-Polar Dielectrics: centres of ⊕ve charge & ⊖ve charge coincide, Therefore Non-polare molecules ~~possess~~ donot possess permanent dipole moments. such dielectrics

6

are called Non-polar Dielectrics

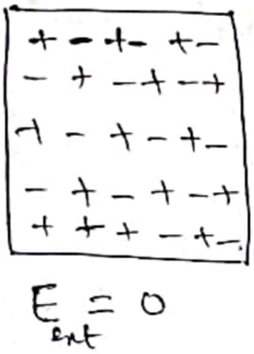
eg: H_2 CO_2 N_2, O_2 CH_4 etc, in which ⊕ve & ⊖ve centres coincides makes zero seperation, the dipole moment of such molecules is zero.

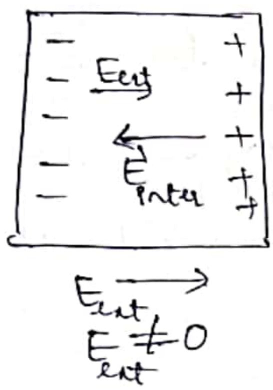
Symmetric molecules.

$\varepsilon_r = 1$ to 2.2

In the absence of external Electric field ($\vec{E}$) dipole moment is zero. However in the presence of $\vec{E}$, the polarization of the dielectric. (seperation of +ve in the dirn of $\vec{E}$ & -ve in the opposite direction) takes place. These induced charges produce an internal electric field that opposes the external electric field.

The result is that there is a reduction in external electric field within dielectric





Displacement of charges takes place

Resultant $E = E_{ext} - E'_{internal}$

Polarization: The dipole moment develope per unit volume in an dielectric when placed in external electric field is called polarization ($\vec{P}$), also called polarization density.

The Induced dipole moment is in the direction of the field & is proportional to the field strength.

$$\text{Polarization} = \frac{\text{Induced dipole moment}}{\text{volume}}$$

$$P = \frac{\mu}{V}$$

[for unit volume V=1]

If N-Atoms are present $\quad P = N\mu$

Induced dipole moment $\quad \mu \propto E_{ext\ field}$

$$\mu = \alpha E$$

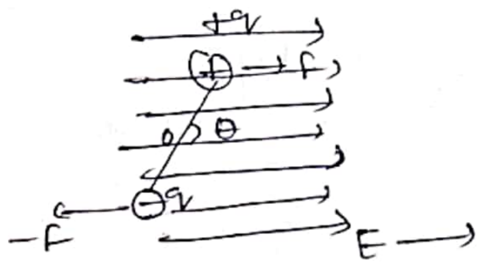
where α is proportionality const called polarizability.

$$\therefore \quad P = N\mu = N\alpha E.$$

$$\langle P = N\alpha E \rangle$$

| $P = \varepsilon_0 \chi_e E$
$\chi_e \rightarrow$ electric susceptibility

In case of polar molecules even though net dipole moment is present orientation random, when we apply uniform electric field experiences torque.

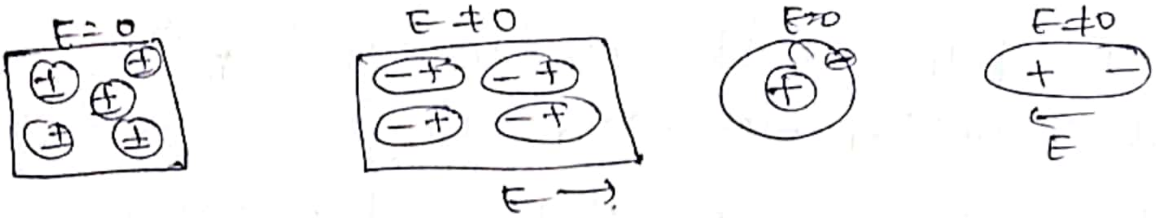


$$\text{Torque} = \mu E \sin\theta$$

θ is angle b/w μ & E

Types of Electric polarization

1) Electronic polarization :- Electronic Polarization occurs due to the displacement of the ⊕ve charged nucleus & ⊖ve charged electrons of an atom in opposite direction of $\vec{E}$.



$P_e = N \alpha_e E_{ext}$

$P_e \rightarrow$ electronic polarization

$\alpha_e \rightarrow$ electronic polarizibility which is Independent of Temp

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

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

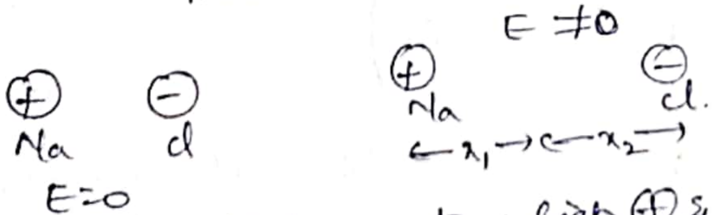
$$\varepsilon_r = 1 + \frac{N\alpha_e \cancel{E}}{\varepsilon_0 \cancel{E}}$$

$$\varepsilon_r = 1 + \frac{N\alpha_e}{\varepsilon_0}$$

$\alpha_e = 4\pi\varepsilon_0 R^3 \rightarrow$ enclosed in a sphere of charge

or $\quad P_e = N(4\pi\varepsilon_0 R^3)E \rightarrow$ electronic polarization $\rightarrow (1)$

2). Ionic/Atomic Polarization :- occurs due to the displacement of cation & anion ($\oplus$ & $\ominus$ ions) in opposite direction by an electric field. occurs only in ionic solids.



x_1, x_2 is the distance to which $\oplus$ & $\ominus$ve ions move apart from eq^m position

Interatomic distance changes when E is applied.

For the ion : Restoring force $F \propto x_1$

$F = \beta_1 x_1 \quad | \ \beta_1 = m\omega_0^2$ (KCl)

$eE = m\omega_0^2 x_1 \rightarrow ① \Rightarrow x_1 = \frac{eE}{m\omega_0^2}$

Ully ⊖ve Ion $F = \beta_2 x_2 \quad | \ \beta_2 = M\omega_0^2$

$F = M\omega_0^2 x_2 \rightarrow ② \Rightarrow x_2 = \frac{eE}{M\omega_0^2}$

Add ① & ②

$$x_1 + x_2 = \frac{eE}{\omega_0^2}\left\{\frac{1}{m} + \frac{1}{M}\right\}$$

$$\mu_i = e(x_1 + x_2)$$

Induced dipole moment = magnitude x displacement

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

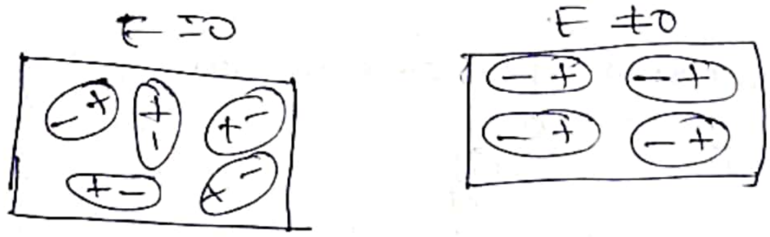
$\omega_0 \rightarrow$ Lar frequencies of constituent ions

$$\mu_i = \alpha_i E$$

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

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

3). Orientation Polarization: arises due to presence of Polar molecules in the dielectric medium.



when E is applied +ve portion align themselves in the direction of field & ⊖ve in opposite direction, this kind of Polarization is called as orientation polarization.

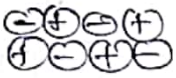
this depends on Temp. when T increases thermal energy tends to randomize alignment.

$$P_o = N \alpha_o \vec{E}$$

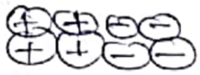
$$\alpha_o = \frac{\mu^2}{3K_BT} \qquad \therefore \left\langle P_o = \frac{N\mu^2 E}{3K_BT} \right\rangle \rightarrow (3)$$

By Langevin's theory
net intensity of magnetisation

Space charge polarization : occurs due to diffusion of ions, along the electric field direction & giving rise to ch redistribution of charges in dielectrics. this occurs only in ferrites & semiconductors & will be very small



$E=0$



$E \neq 0$

$$P_s = N\alpha_s \vec{E} \rightarrow (4)$$

Total polarization :

$$P = P_e + P_i + P_o + P_s = N(\alpha_e + \alpha_i + \alpha_o + \alpha_s)\vec{E}$$

$$= N\left[4\pi\varepsilon_0 R^3 + \frac{e^2}{\omega_0^2}\left\{\frac{1}{m} + \frac{1}{M}\right\} + \frac{\mu^2}{3K_BT}\right]\vec{E} \longrightarrow (5)$$

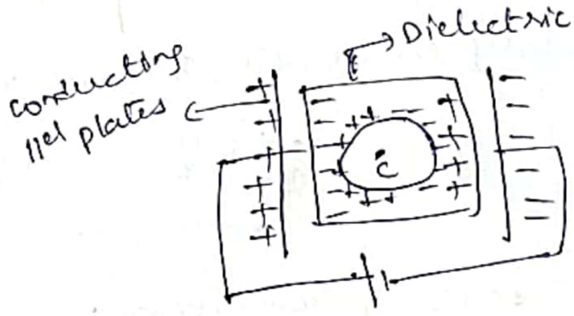
Clausius - Mosotti relation

Internal/Local field : when a dielectric is kept in an external field (E), two fields are excerted due to

(i) External field (ii) Field created by the neighbouring dipoles

These long range coulomb force which are created due to the dipoles are called Local field or Internal field

Consider a Dielectric solid in an External field E b/w ||el plates & dipoles are formed in the material.



The Total polarization in dielectric is given by

$$P = P_e + P_i + P_o + P_s$$

Here we are considering a solid P_e → electronic polarization is dominant

$$\therefore \quad P = P_e = N\alpha_e E_i \rightarrow (1)$$

N → No of atoms or molecules or dipoles per unit volume

E_i → Local electric field.

WKT $$E_i = E_{external} + \frac{P}{3\epsilon_0} \rightarrow \text{(field due to dipoles)}$$

$$E_i = E_{ext} + \frac{P}{3\epsilon_0} \rightarrow (2).$$

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

i.e, $P = (\epsilon_0\epsilon_r - \epsilon_0)E \Rightarrow (\epsilon - \epsilon_0)E$

$$\therefore \quad E = \frac{P}{\epsilon - \epsilon_0} \rightarrow (3)$$

substitute (3) in (2)

$$E_i = \frac{P}{\epsilon - \epsilon_0} + \frac{P}{3\epsilon_0} \rightarrow (4)$$

$$P = N\alpha_i E_i$$

From (1)

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

Rewrite (E_i)

$$E_i = \frac{P}{\varepsilon-\varepsilon_0} + \frac{P}{3\varepsilon_0}$$

$$\frac{P}{N\alpha} = \frac{P}{\varepsilon-\varepsilon_0} + \frac{P}{3\varepsilon_0}$$

(take LCM)

$$\frac{P}{N\alpha} = \frac{P(3\varepsilon_0) + P(\varepsilon-\varepsilon_0)}{3\varepsilon_0(\varepsilon-\varepsilon_0)}$$

$$\frac{\cancel{P}}{N\alpha} = \frac{\cancel{P}(3\varepsilon_0 + \varepsilon - \varepsilon_0)}{3\varepsilon_0(\varepsilon-\varepsilon_0)}$$

$$\frac{3\varepsilon_0}{N\alpha} = \frac{2\varepsilon_0 + \varepsilon}{(\varepsilon-\varepsilon_0)}$$

$(\varepsilon = \varepsilon_0 \varepsilon_r)$ medium, freespace

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

$$\frac{3\varepsilon_0}{N\alpha} = \frac{(2+\varepsilon_r)\cancel{\varepsilon_0}}{(\varepsilon_r-1)\cancel{\varepsilon_0}} \longrightarrow (5)$$

Reverse the eqn $\frac{N\alpha}{3\varepsilon_0} = \frac{\varepsilon_r - 1}{2+\varepsilon_r} \longrightarrow (6)$

eqn (6) represents clausius Mosotti eqn relates microscopic parameters (atomic polarizibility) α with the microscopic dielectric const ε_r

FERROELECTRICS

A new varilty of charcteristics, new classes of dielectric material called ferroelectric, piezoelectric & pyroelectric ceramics.

→ Ferroelectric materials are charecterized by the presence spontaneous dielectric polarization which doesnot need any external electric field to get them polarized. & direction of spontaneous polarisation can be reversed by reversing the dirⁿ of Electric field.
ex:- Rochelle salt (sodium Potassium Tetrate $NaKC_4H_4O_6 \cdot 4H_2O$)

$E = 0$ ↑↑↑↑
$P \neq 0$ ↑↑↑↑

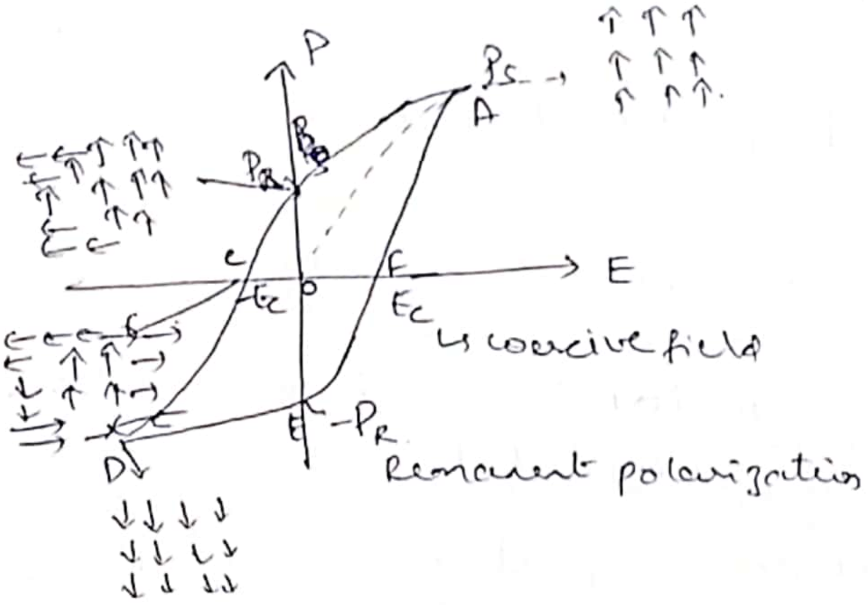
→ There are pre-existing dipoles in these materials even in the absence of external electric field.
becoz there is minor deviation from crystallographic symmetry or inherent asymmetry in the crystal structure of these materials.

→ As a consequence of spontaneous polarization the Mechanism of orientation polarization dominates over all other mechanisms

→ these are ex- of Non-linear dielectrics giving rise to ferroelectric hysteresis when polarization is plotted against electric field.
The polarization becomes maximum when all the domains become parallel to the direction of the applied field

→ The generation of current in response to the application of force is called piezoelectricity

Ferroelectric Hysterises



At O. $E=0$, $P=0$,

At A $E_{max}=E$, $P=P_s$ (saturation polarization)

At B $E=0$, $P=P_R$ (Remenent polarization)

At C $E=-E_c$ $P=0$ E_c (co-ercive field)

At D $E=-E_{max}$ $P=-P_s$

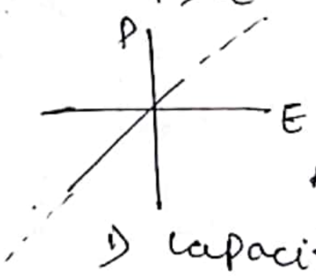
At E $E=0$ $P=-P_R$

At F $E=E_c$ $P=0$

It exhibits ferro-electric property below curie Temp

curie Temp (T_c) → $T<T_c$ ⇒ ferroelectric material
→ $T>T_c$ ⇒ Piezoelectric material

$T>T_c$



$$\chi = \frac{c}{T-T_c}$$

Applications

1) Capacitors, Non-volatile memory
2) Electro-optic materials for data storage applications
3) Thermistors, oscillators & filters, light deflectors, modulators
4) Switches known as transchargers or transpolarizers
5) Piezoelectrics for ultrasound imaging & actuators