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-: HAND WRITTEN NOTES:-

OF

1

# ELECTRONICS & COMMUNICATION ENGINEERING

-: SUBJECT:-

# ELECTRICAL MATERIALS

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Crystal structure } Obj

Dielectric properties of materials } Obj + conv.

Magnetic properties of materials }

Conductors / Insulators / S.C. } conv. + obj

- Conductors → Super conductor

- Insulators → Ceramics

- S.C. → Hall effect.

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- \* Crystal Structure :-

- Chemical bonds

- Atomic arrangement in solids

- Cubic crystal structure }

- Miller Indices }

- Bravais crystal system }

- Structural Imperfections.

- \* Chemical Bonds :-

- Binding forces b/w atoms or molecules are known as chemical bonds.

There are two types of chemical bonds

- 1) Primary
- 2) Secondary

**Primary Bond:** These bonds are having higher bonding energy. for ex. covalent bond, Ionic bond and metallic bond.

**Secondary Bond:** These bonds are having

lesser bonding energy as compare to primary bonds. for ex: Vanderwaal's bond & hydrogen bond. etc

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Ionic bond:- It is bond resulting from electrostatic interaction of oppositely charged ions. by transfer of e<sup>-</sup> from one to another.

Ionic bond formed particularly b/w left hand side & RHS. of periodic table is strongly ionic.

Group I - Alkali elements

Li, Na, K, Rb, Cs, Fr

Group VII - Halogens

F, Cl, Br, I

for ex:- Alkali Halides (Ionic molecules)

NaCl, KCl

Properties of Material having Ionic bond.

Higher Strength.

Higher Hardness.

Higher melting point

Electrically Insulator

Brittle

• Covalent Bond :- These bonds are formed due to sharing of  $e^-$ .

Properties of material having covalent bond:-

- Very Hard.
- Very high melting pt.
- Very brittle.
- Conductor : Tin

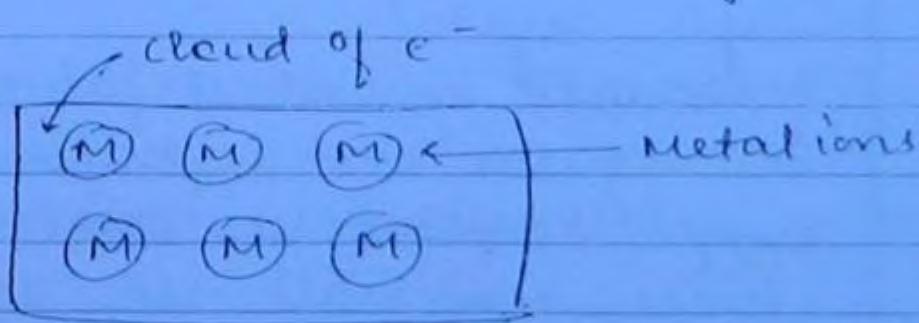
Insulator : Diamond

S.C. : Si, Ge.

• Metallic Bond:-

This bond is the characteristic of elements having small no. of valence  $e^-$  so that they can be easily released.

Metallic bond can be considered as metal containing a periodic structure of  $+ve$  ions surrounded by a cloud of  $e^-$ .

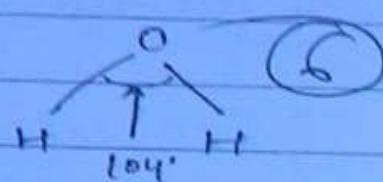


• Vanderwaal's bond :-

Dipole interaction b/w molecules or atoms is due presence of vanderwaal's force of attraction ex@ inert gases (He, Ne, Ar, Kr).

② dipole interaction b/w asymmetrical molecules for ex:  $\text{H}_2\text{O}$ .

Hydrogen bond is a strong type of vanderwaal's bond.



Atomic arrangement in solids :-

- crystallinity.
- single crystal
- Poly crystalline  $\rightarrow$  grains
- Amorphous
- Epitaxial

Crystallinity :-

Property of solid in which atoms or molecules are arrange in the regular or periodic manner is called crystallinity.

Single crystal:

Material in which atomic arrangement is regular or periodic is called single crystal material. ex: quartz. These materials are anisotropic material.

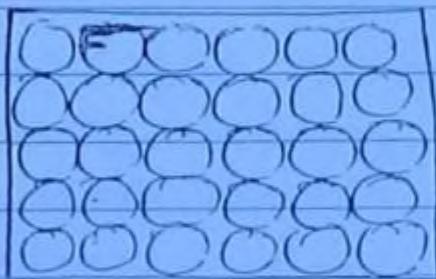
Poly crystalline

It consist of grains with in which atomic arrangement is regular.

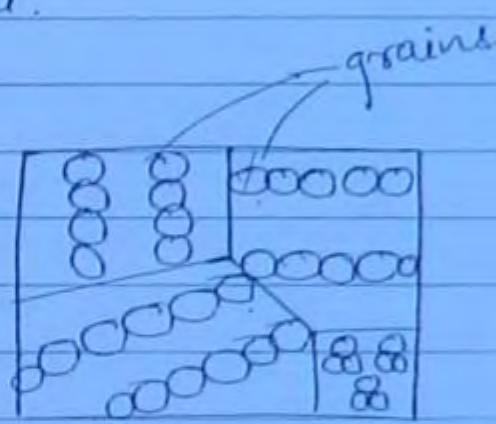
but showing irregularities in form one grain to another.

These materials are isotropic.  
ex: polycrystalline Si.

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Single crystal material



Polycrystalline material

### Isotropic & Anisotropic material

Anisotropic: If properties of materials depend on the direction in which they are measured. are known as anisotropic material ex. Quartz.

Isotropic: If properties of materials are independent of direction in which they are measured then material is called isotropic.

Polycrystalline materials are isotropic because of random distribution of grains.

Amorphous :- Atoms upto  $r^*$  nearest neighbours are arranged periodically.

but the atoms which are away from the nearest atoms are found to arranged randomly. (8)

where the atoms are not given opportunity to arrange in orderly manner, ~~and~~ amorphous material may be formed - for ex. supercooled state of  $\text{SiO}_2$  correspond to glass.

(amorphous) whereas on one "Annealing (slow cooling & heating)".

$\text{SiO}_2$  <sup>crytallizes into</sup> Quartz (single crystal material).

In other cases the molecules may be extremely long & irregular in shape, so that orderly arrangement may not be obtained as in case of polymers.

#### • Epitaxial :-

Epitaxial represents growth of a layer of Si on a substrate

#### • Crystal Structure :

Unit cell :- It represents minimum area cell in 2-D and minimum volume cell in 3-D by repetition of which a crystal may be formed.

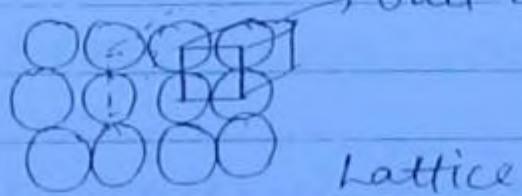
## Parameters of unit cell :-

1. Unit cell dimension
2. Angle b/w axis
3. No. of atom per unit cell.
4. Atomic Packing factor (APF)

$$APF = \frac{\text{sum of atomic volume}}{\text{Volume of unit cell}}$$

5. Coordination No. :- It represents no. of atoms which are in physical contact with a particular atom.

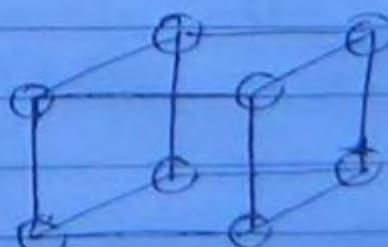
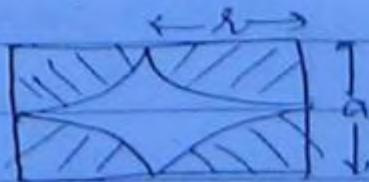
- Lattice :- A lattice is a periodical arrangement of unit cell.



- Cubic Crystal Structure :-

- Simple cubic
- Body centered cubic
- Face centered cubic
- Diamond cubic.

- Simple cubic :



a simple cubic there are 8 atoms at 8 corners of the cube

No. of atom per unit cell =  $8 \times \frac{1}{8}$  10

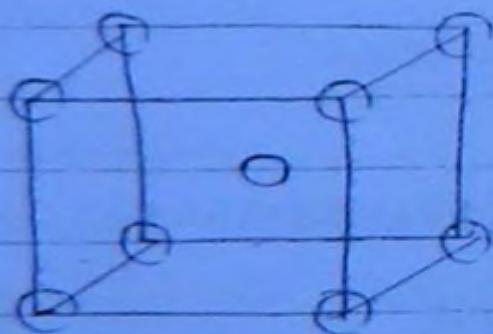
= 1

Atomic packing factor (APF) =  $\frac{1 \times \frac{4}{3}\pi r^3}{a^3}$   
= 0.52.

Coordination no. = 6

ex: of simple-cubic : Mn, Pelonium, Fluorite etc

Body centered cubic :- (BCC)



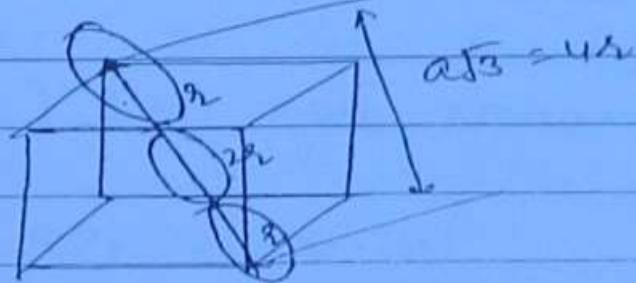
a BCC there are 8 atoms at 8 corners of the cube and 1 atom at the center of unit cell.

In BCC atoms are in physical contact along body diagonal.

$$\text{No. of atoms / unit cell} = \frac{8 \times 1}{8} + 1 \\ = 2$$

$$\text{APF} = \frac{2 \times \frac{4}{3} \pi r^3}{a^3} \quad (1) \quad \therefore r = \frac{a\sqrt{3}}{4}$$

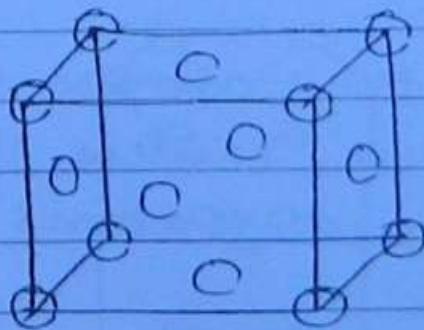
$$= 0.68$$



Coordination no. = 8

ex: Li, Na, K, Cr, Fe ( $\alpha$ -iron), Fe ( $\delta$ -iron) etc.

Face centered cubic (FCC):

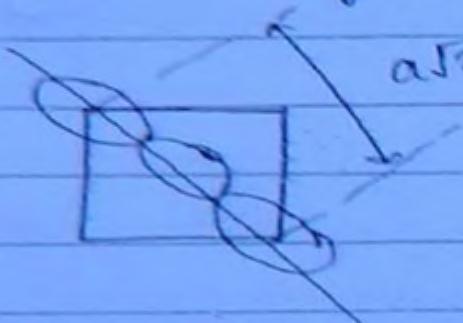


$$\text{No. of atom / unit cell} = 8 \times \frac{1}{8} + 6 \times \frac{1}{2} \\ = 4$$

$$\text{APF} = \frac{4 \times \frac{4}{3} \pi r^3}{a^3} \\ = 0.74$$

$$\therefore r = \frac{a\sqrt{2}}{4}$$

In FCC atoms are in physical contact along  $\frac{1}{2}$  face diagonal.



(12)

FCC is also known as CCP (cubic closed pack).

coordination no. = 12.

Ex: Ag, Au, Al, Cu, Ni, Pb, NaCl, Pt, Fe (X-ray) etc.

#### \* Diamond cubic (DC):

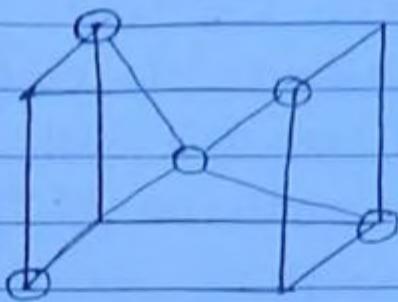
In diamond cubic, there are ~~the~~ 18 atoms.

8 atoms are at 8 corners of the cube

6 atoms at the centers of 6 faces of the cube and 4 atoms are inside.

$$\begin{aligned} \text{no. of atoms / unit cell} &= 8 \times \frac{1}{8} + 6 \times \frac{1}{2} + 4 \\ &= 8 \end{aligned}$$

This structure is also known as "tetrahedral structure".



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Coordination no. = 4

Ex: Si, Ge, C, Diamond, GaAs etc.

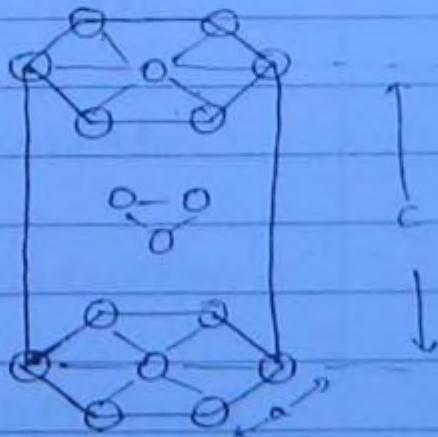
$$r = \frac{a\sqrt{3}}{8}$$

$$APF = 0.34$$

This structure is also known as "Zinc Blend" structure

Group 3,5 compound have Zinc Blend structure

Hexagonal closed Packing (HCP) :-



In HCP, there are 12 atoms at 12 corners of the top & bottom Hexagon.

2 atoms at the centers of top &

bottom Hexagon.

3 atoms are inside

(14)

$$\text{no. of atoms/unit-cell} = \frac{12 \times 1}{6} + \frac{2 \times 1}{2} + 3 \\ = 6$$

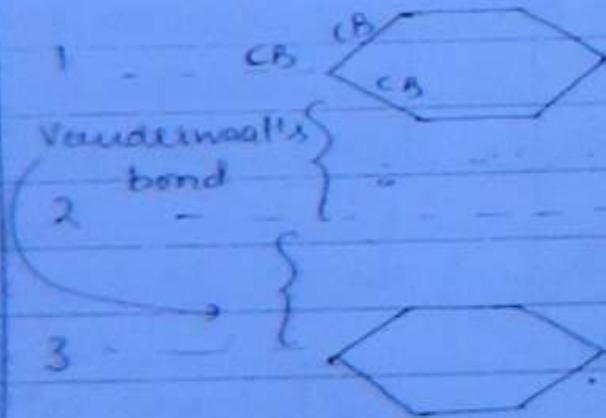
$$APF = 0.74$$

$$\frac{c}{a} = \frac{\text{max}^m \text{ dimension}}{\text{min}^m \text{ dimension}} = 1.63.$$

Ex: Be, Cd, Co, Zn, Mg etc.

graphite :-

structure of graphite is hexagonal  
but it is not HCP as there is  
no center atom in top & bottom  
hexagon.



each carbon atoms have 4 valence.

3 of these  $e^-$ s are used in forming covalent bond with adjacent atom in the same layer. The 4<sup>th</sup>  $e^-$  is feed to vander over the surface of layer making graphite a electrical conductor. weak bonding forces b/w layers are called vander waal's forces. because these forces are weak, the layers can slide on each other. the sliding property of layers gives graphite its softness for writing and lubricating properties.

(BS)

### Comparison of graphite & diamond

	Diamond	Graphite
• Hardness	Extremely hard	Soft
• Trans-	transparent	opaque
parency		
• Electrical	Insulator	conductor
Properties		
• Thermal	conductor	Insulator
Properties		
• Structure	Tetrahedral	Hexagonal { ≠ HCP}

## \* Comparison of different crystal structure

Structure	No. of atoms/unit cell	APF
DC	8	0.34
SC	1	0.52
BCC	2	0.68
FCC	4	0.74
Packing of atom [ABC ABC ABC ...]		
HCP [AB AB ...]	6	0.74

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Coordination no.	atomic radius (r)	Examples
4	$\frac{a\sqrt{3}}{8}$	Ge, Si, C, Diamond, GaAs etc.
6	$\frac{a}{2}$	Mn, Polonium, Fluorspar
8	$\frac{a\sqrt{3}}{4}$	Li, Na, K, Cu, Fe(α, δ)
12	$\frac{a\sqrt{2}}{4}$	Au, Ag, Al, Cu, Ni, Pt, Pb, NaCl, Fe(γ)
18	$\frac{c}{a} = 1.63$	Be, Mg, Zn, Cd, Co. etc.

Q when BCC iron is heated, it changes to FCC iron resulting in.

- (a) increase in volume
- (b) contraction in volume
- (c) NO change in volume
- (d) Crack in the material.

(B)

Ans (b).



$$\text{micVol} = \text{APF} = 0.68 \quad 0.74$$

1.8 unitcell

Q consider the statement related to FCC structure

- 1. coordination no. is 12.
- 2. APF is 0.74
- 3. there is an atom at the body centre of the unit cell

which of the statement are correct

Ans

1 2 2

Q which of the following statement are true for diamond structure

- 1. coordination no. is 4.
- 2. packing fraction is 0.34
- 3. Cu crystallizes into diamond structure

Ans 1 2 2.

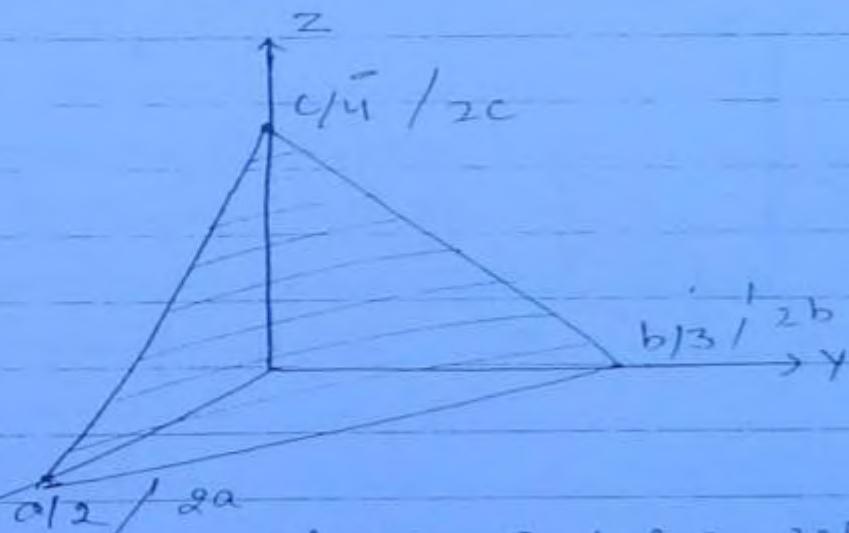
8 In a Si crystal, the arrangement of atoms repeats periodically. This type of material is classified as

- (a) Amorphous & non-crystalline
- (b) Non crystalline & epitaxial
- (c) Epitaxial & single crystal.
- (d) Amorphous & single crystal.

(q)

Ans. (c).

\* Miller Indices:-



where  $a, b \& c$  represents unit cell dimension along  $x, y \& z$  axis respectively

\* Steps to determine Miller Indices:

1. Determine intercepts made by plane on 3 axes.

$$a/2, b/3, c/4 / 2a, 2b, 2c$$

2. Express intercepts as multiples of

unit cell dimension

$$\frac{1}{2}, \frac{1}{3}, \frac{1}{4} / 2, 3, 4$$

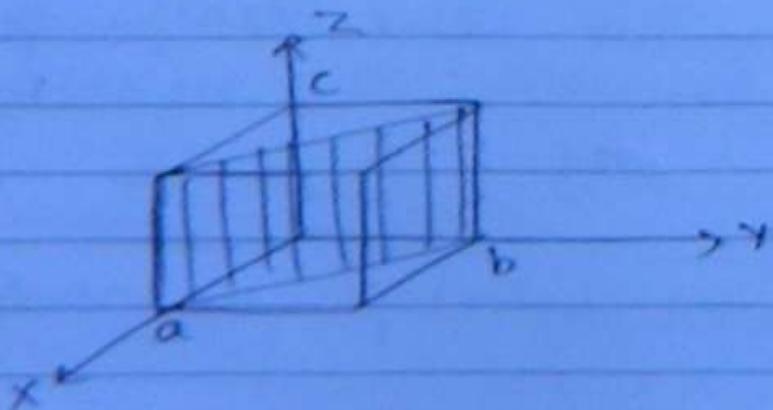
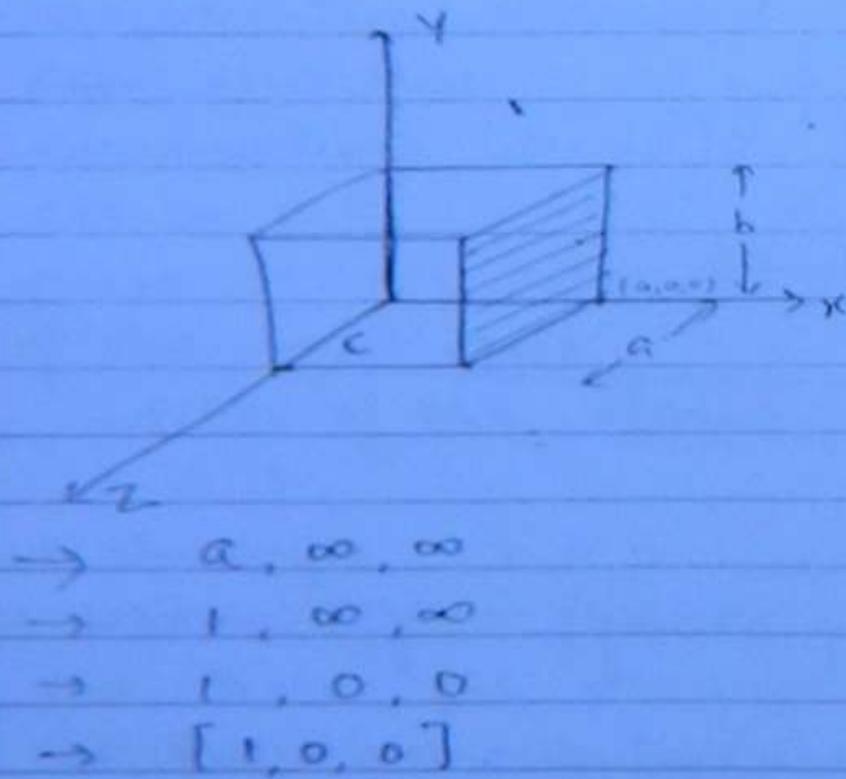
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3. Get reciprocals of multiples.

$$2, 3, 4 / \frac{1}{2}, \frac{1}{3}, \frac{1}{4}$$

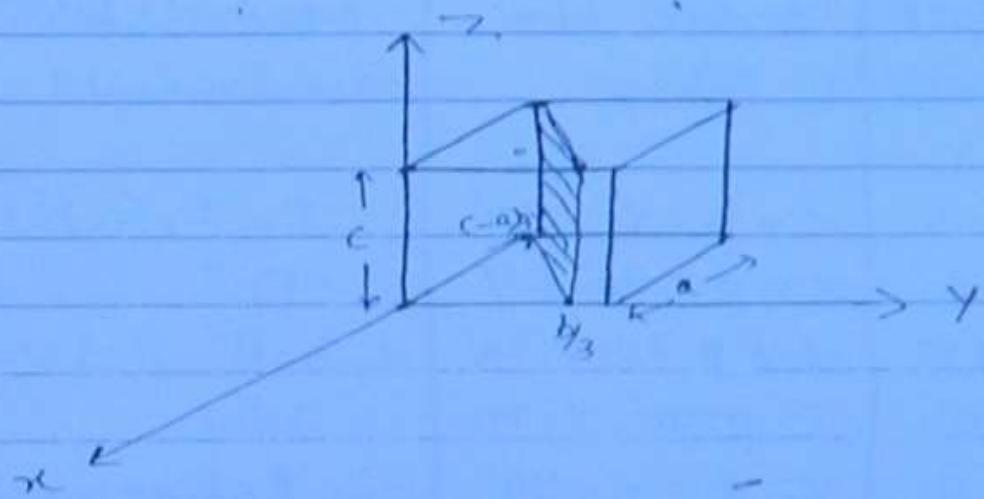
4. Reduce reciprocals to smallest set  
of integers.

$$[2, 3, 4] / [6, 4, 3]$$

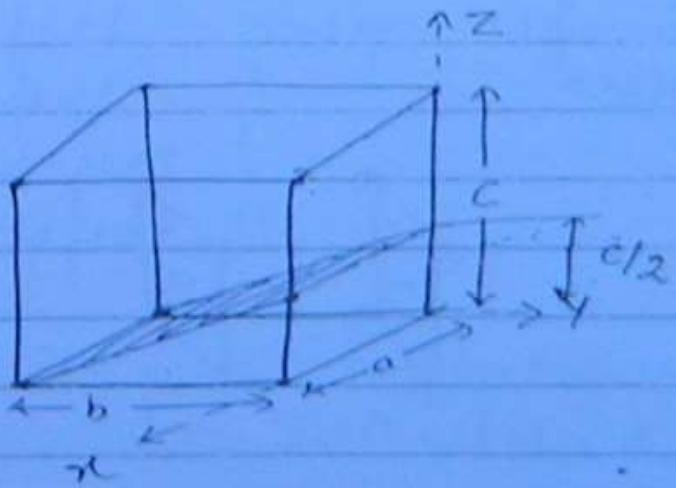


- $\rightarrow a, b, \infty$   
 $\rightarrow 1, 1, \infty$   
 $\rightarrow 1, 1, 0$   
 $\rightarrow [1, 1, 0]$

(21)



- $\rightarrow -a, b/3, \infty$   
 $\rightarrow -1, \sqrt{3}, \infty$   
 $\rightarrow -1, 3, 0$   
 $\rightarrow [-1, 3, 0]$   
 $\rightarrow [-1, 3, 0]$



- $\rightarrow \infty, -b, c/2$   
 $\rightarrow \infty, -1, \sqrt{2}$   
 $\rightarrow \infty, -1, 2$   
 $\rightarrow [0, 1, 2]$

# \* Bravais Crystal System

- 7 crystal classes
- 14 Bravais Lattices

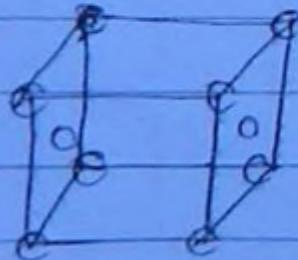
(22)

Crystal class	Unit cell dimension	Angle b/w Axis	Bravais Lattices
Orthorhombic	$a \neq b \neq c$	$\alpha = \beta = \gamma = 90^\circ$	P, I, C, F
Monoclinic	$a \neq b \neq c$	$\alpha = \beta = 90^\circ \neq \gamma$	P, C
Triclinic	$a \neq b \neq c$	$\alpha \neq \beta \neq \gamma \neq 90^\circ$	P
Hexagonal	$a = b \neq c$	$\alpha = \beta = 90^\circ, \gamma = 120^\circ$	P
Tetragonal	$a = b \neq c$	$\alpha = \beta = \gamma = 90^\circ$	P, I
Trigonal / Rhombohedral	$a = b = c$	$\alpha = \beta = \gamma \neq 90^\circ$	P
Cubic	$a = b = c$	$\alpha = \beta = \gamma = 90^\circ$	P, I, F

P → Simple cubic

I → BCC

C →



F → FCC

The unit cell of a certain type of crystal is defined by 3 vectors  $\bar{a}$ ,  $\bar{b}$  &  $\bar{c}$ . The vectors are mutually perpendicular but  $a \neq b \neq c$ . The crystal structure is

- (a) Triclinic
- (b) Tetragonal
- (c) Monoclinic
- (d) Orthorhombic

(d)

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Match List 1 & List 2

List 1

- A. Hexagonal.
- B. Rhombohedral
- C. Triclinic
- D. Monoclinic

List 2

- 1.  $a = b = c$ ,  $\alpha = \beta = \gamma \neq 90^\circ$
- 2.  $a = b \neq c$ ,  $\alpha = \beta = 90^\circ$ ,  $\gamma = 120^\circ$
- 3.  $a \neq b \neq c$ ,  $\alpha = \beta = 90^\circ \neq \gamma$
- 4.  $a \neq b \neq c$ ,  $\alpha \neq \beta \neq \gamma \neq 90^\circ$

\* Structural Imperfections:-

- Point defect → Vacancy
- Line defect → Impurity
- Surface defect
- Volume defect

\* Impurity → substitutional  
↓  
Interstitial

Vacancy defect :-



Vacancy

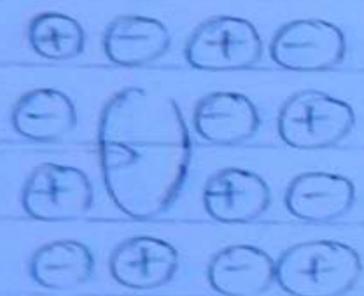
It is a point defect which involves a missing atom with in a crystal structure.

(24)

Schottky defect :- It is a vacancy defect.

It involves ~~a~~ missing pair of the -ve ion with in a crystal structure.

Schottky defect



In a crystal lattice, the vacancies created by the absence of certain atoms are known as

- (a) Frenzel defect
- (b) Pauli's defect
- (c) Frankel defect
- (d) Schottky defect

(d)

# Dielectric Properties of materials

**Dielectrics :-** A dielectric is a non-conducting material which can be polarized by an electric field.

If main f" of non conducting material is to provide electrical insulation then material is called insulator.

If the main f" of non conducting material is storage of charge then material is called dielectric.

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**Parameters of Dielectric :-**

1. Dielectric constant
2. Dipole moment
3. Polarization
4. Polarizability.

**Dielectric constant :-**

It is defined as the ratio of electric flux density to electric field intensity.  
i.e.

$$\epsilon = \frac{D}{E}$$

where  $D$  = flux density ( $C/m^2$ )

$E$  = electric field intensity ( $V/m$ )

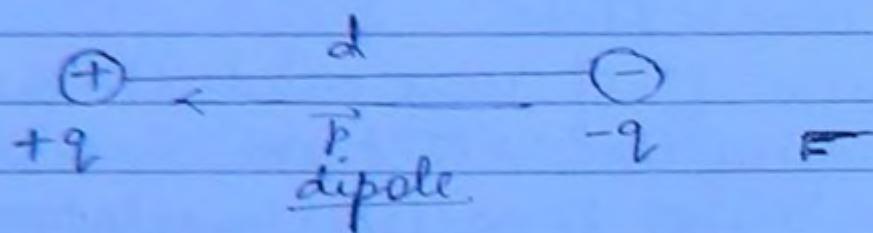
$$\epsilon = \epsilon_0 \epsilon_r$$

where  $\epsilon_0$  = permittivity of free space

$$= 8.85 \times 10^{-12} F/m$$

$\epsilon_r$  = relative permittivity

Dipole : Two opposite charges separated by a distance constitutes an electric dipole



Dipole moment: It is defined as the product of charge & distance of separation.

It is a vector quantity which is directed from -ve charge to +ve charge.  
It mean dipole moment

$$\vec{P} = q\vec{d}$$

Unit → (1) C-m

(2) "Debye"

$$1 \text{ debye} = 3.33 \times 10^{-30} \text{ C-m}$$

Polarization : It is defined as dipole moment per unit volume.

$$P = \frac{\text{polarization}}{\text{volume}}$$

$$P = Np$$

where  $N$  = no. of dipoles per unit volume.

Unit:  $C/m^2$

(27)

Total flux density inside dielectric material under the influence of electric field is due to 2 components.

1. External electric field

2. Polarization inside dielectric material.

$$D = \underbrace{\epsilon_0 E}_{\text{flux density due to applied E-F.}} + \underbrace{P}_{\text{flux density due to polarization}}$$

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

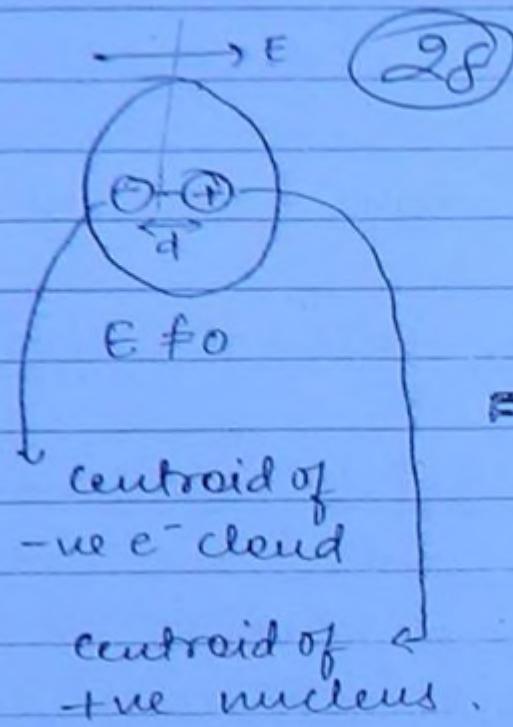
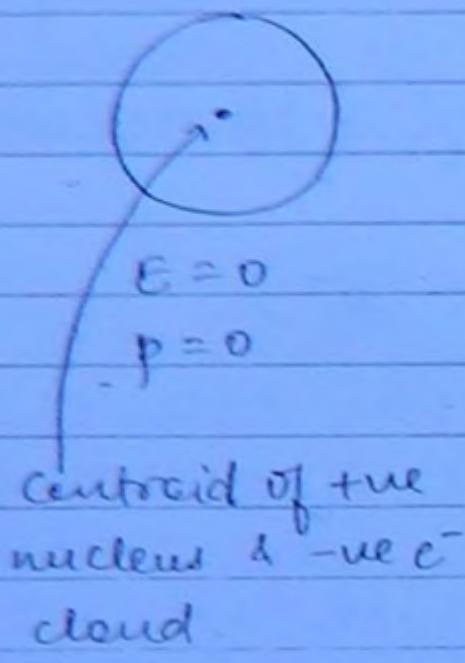
$$\Rightarrow P = \epsilon_0 (\epsilon_r - 1) E$$

$$P = \epsilon_0 \chi_e E$$

Where  $\chi_e$  = dielectric susceptibility.  
 $= \epsilon_r - 1$  (unit less)

Polarizability: - ( $\alpha$ )

# Polarizability ( $\alpha$ ) :-



$$\rightarrow p \propto d \quad (1)$$

$$\rightarrow d \propto E \quad (2)$$

from (1) & (2)

$$p \propto E$$

$$[ p = \alpha E ]$$

where  $\alpha$  represent polarizability

$$\begin{aligned} \alpha &= \frac{p}{E} = \frac{Qd}{(v/d)} \\ &= \left(\frac{Q}{v}\right) \cdot d^2 \end{aligned}$$

$$= c \cdot d^2$$

Unit  $\rightarrow F \cdot m^2$

Relation b/w ' $\chi_e$ ' &  $\alpha$ .

As we know,

$$\begin{aligned} P \cdot P &= NP \\ &= N\alpha E \end{aligned}$$
 (1)

(29)

Also,

$$P = \epsilon_0 \chi_e E \quad (2)$$

F

from (1) & (2)

$$\begin{aligned} N\alpha E &= \epsilon_0 \chi_e E \\ \Rightarrow \alpha &= \frac{\epsilon_0 \chi_e}{N} \quad \text{for gaseous dielectric only.} \end{aligned}$$

- Q A homogeneous slab of lossless dielectric material is characterized by an electric susceptibility of 0.12 & carries a uniform flux density within it of  $1.6 \text{ nC/m}^2$ . Find E, P, p & voltage across dielectric if there are  $2 \times 10^{19}$  dipoles per cubic meter & distance b/w opposite surfaces of dielectric is 2.54 cm.

Sol?

$$\chi_e = 0.12$$

$$\text{Doseeto } D = 1.6 \text{ nC/m}^2$$

$$\chi_e = \epsilon_r - 1$$

$$0.12 = \epsilon_r - 1$$

$$\epsilon_r = 1.12$$

$$N \text{ } \textcircled{w} = 2 \times 10^{19}$$

$$d = 2.54 \text{ cm}$$

$$E = \frac{D}{\epsilon} = \frac{D}{\epsilon_0 \epsilon_r}$$

$$\begin{aligned} &= \frac{1.6 \times 10^{-9}}{8.85 \times 10^{-12} \times 1.12} \\ &= 161.4 \end{aligned}$$

$$p = q \times d$$

$$= 1.6 \times 10^{-19} \times \frac{2.54}{100}$$

$$\rho \propto P = 60 \times e E$$

(30)

$$= 1.71 \times 10^{-10}$$

$$P = N p$$

~~$$p = 2 \times 10^{19} \times 1.6 \times 10^{-19} \times 2.54 \times 10^{-2}$$~~

~~$$\Phi =$$~~

$$p = \frac{P}{N} = 8.55 \times 10^{-30} \text{ C-m}$$

~~$$V = E \cdot d = -4.09 \text{ V}$$~~

\* Mechanism of Polarization :

1. Electronic Polarization
2. Ionic Polarization
3. Orientational Polarization
4. Space charge / Interfacial Polarization.

. Electronic Polarization

It results from the displacement of -vely charge  $e^-$  cloud w.r.t. +vely charge nuclear

This type of polarization is found in the materials having no interaction among the molecules  
for ex. Rare gases

Polarizability is given by

$\alpha_e$  = electronic polarizability

$$[\alpha_e = 4\pi \epsilon_0 R^3] \quad (31)$$

where  $R$  = atomic radius

$$\alpha_{He} < \alpha_{Ne} < \alpha_{Ar} < \alpha_{Kr} < \alpha_{Xe} < \alpha_{Rn}$$

Electronic polarization is independent of temp.

### Induced Polarization

$$P_e = N \rho i d \quad (1) \\ = N \alpha_e E$$

$$\text{Also, } P = \epsilon_0 X_e E$$

$$\Rightarrow N \alpha_e E = \epsilon_0 (\epsilon_r - 1) E$$

$$\Rightarrow N (4\pi \epsilon_0 R^3) = \epsilon_0 (\epsilon_r - 1)$$

$$[\epsilon_r = 1 + 4\pi N R^3]$$

Q. the no. of dipole in volume of one cubic meter of hydrogen gas is  $9.8 \times 10^{26}$ . the radius of hydrogen atom is  $0.53 \text{ \AA}$ . calculate  $\alpha_e$  &  $\epsilon_0$ .

Dot

$$R = 0.53 \text{ nm}^{\circ}$$

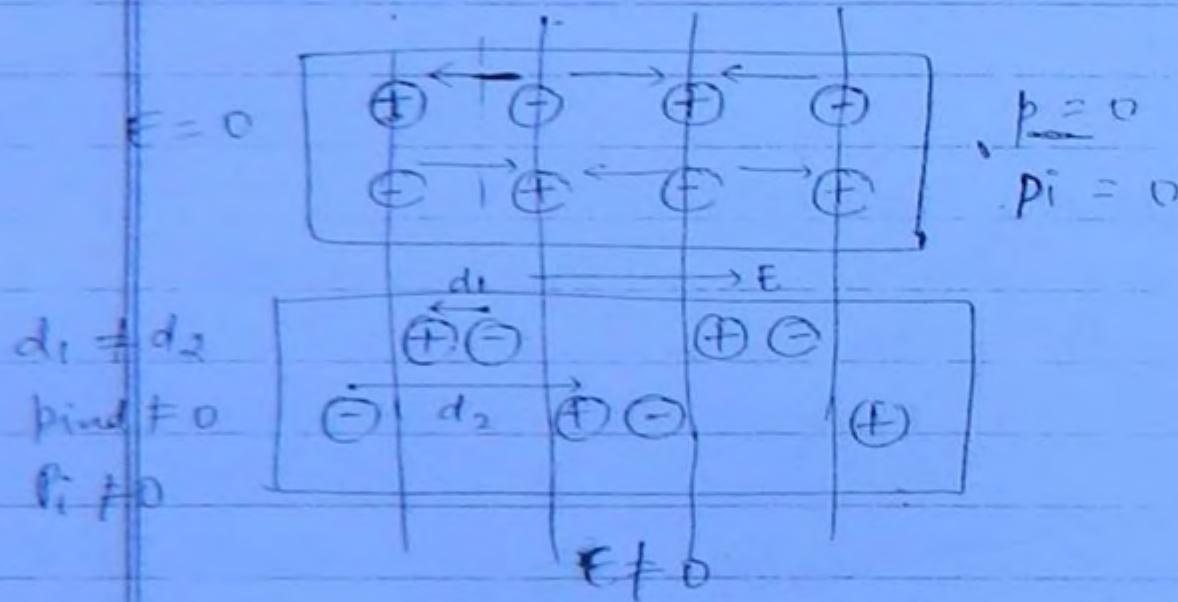
$$N = 9.8 \times 10^{26}$$

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$$\alpha_c = 4\pi \epsilon_0 R^3$$
$$= 1.66 \times 10^{-41} \text{ F-m}^2$$

$$\epsilon_r = 1 + 4\pi N R^3$$
$$= 1.0018$$

### Ionic Polarization :-



It occurs in ionic materials in which the +ve & -ve ions get displaced in opposite direction.

This type of polarization is found in the materials having ionic bonds b/w dissimilar atoms.

for ex:- Alkali Halide (NaCl, KCl etc)

- The ionic polarizability measure the shift of ions relative to each other.  
this type of polarization is also known as molecular polarization.
- Ionic polarization is also independent of temp.
- Total polarization is given by the sum of electronic + ionic polarization

$$P = P_i + P_e$$

$$= N \alpha_i E + N \alpha_e E$$

$$P = N (\alpha_i + \alpha_e) E$$

(33)

### Ionic polarizability,

$$\alpha_i = \frac{q^2}{d^2 Y}$$

where  $q$  = charge on ion

$d$  = distance of separation

$Y$  = Young Modulus.

- for most of the materials Ionic polarizability is less than electronic polarizability.

$$\alpha_i = \frac{\alpha_e}{10}$$

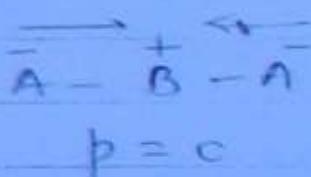
1

## Orientational Polarization:-

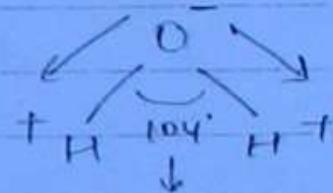
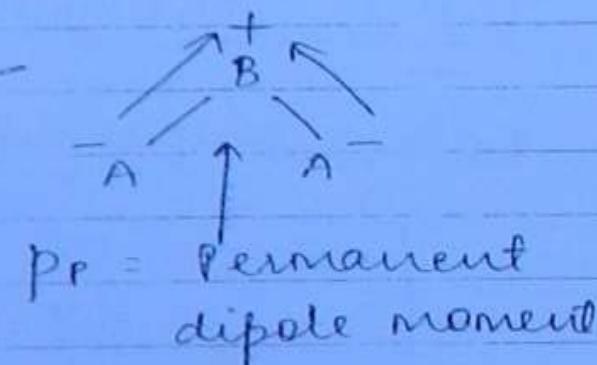
This type of polarization is found in the material having partial ionic bond. It means covalent bonds.

This type of polarization is found in the materials having molecules with asymmetrical nature. for ex: (water)  $\text{H}_2\text{O}$ ,  $\text{H}_2\text{S}$ ,  $\text{NO}_2$ ,  $\text{CO}$ ,  $\text{NO}_3^-$ ,  $\text{CH}_3\text{Cl}$  etc.

$A_2B$



$O=C=O$



Permanent dipole moment :-

Dipole moment due to orientation of molecule is known as permanent dipole moment.

$$\begin{aligned} P_0 &= \frac{Np^2 \cdot E}{3kT} \\ &= N\alpha_0 E \end{aligned}$$

$$\Rightarrow \alpha_0 = \frac{p_p^2}{3kT}$$

(33)

It is inversely proportional to temp.  
and directly proportional to square of  
permanent dipole moment.

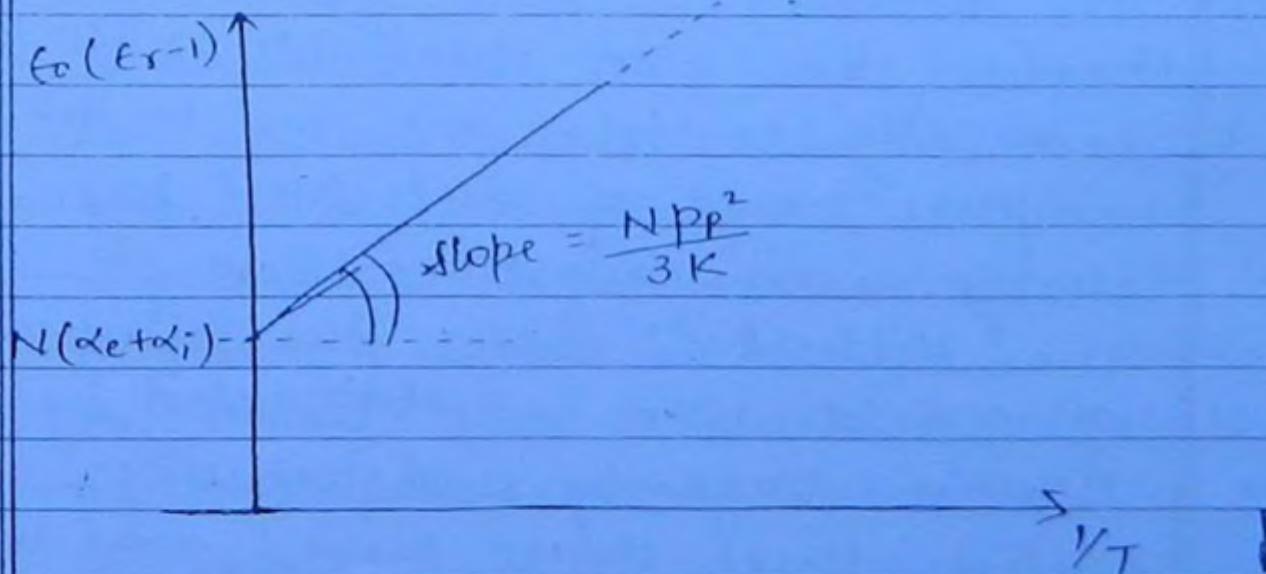
Total polarization,

$$P_T = P_e + P_i + P_o$$

$$\Rightarrow = N(\alpha_e + \alpha_i + \alpha_0) E$$

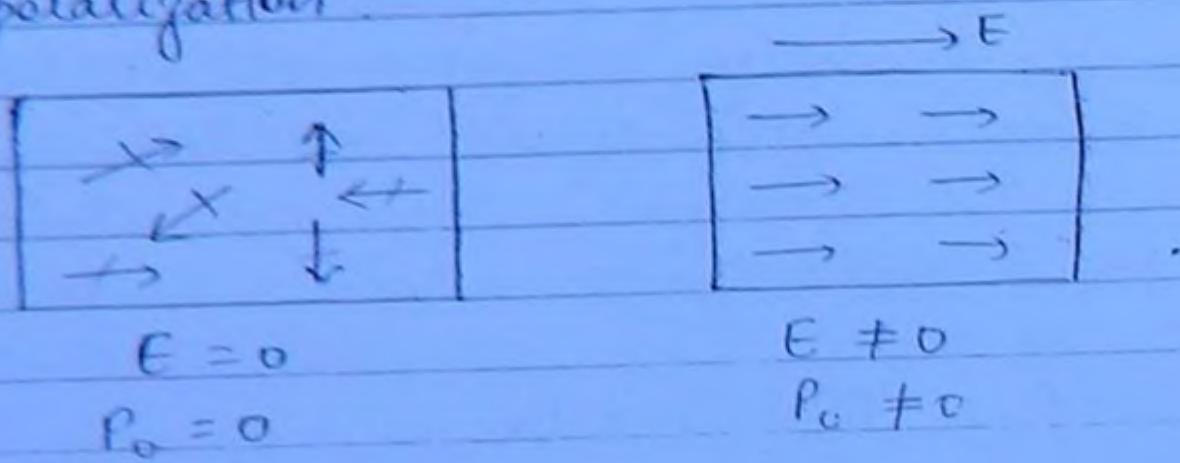
$$\epsilon_0 \times E = N \left( \alpha_e + \alpha_i + \frac{p_p^2}{3kT} \right) E$$

$$\epsilon_0 (\epsilon_r - 1) = N \left( \alpha_e + \alpha_i + \frac{p_p^2}{3k} \cdot \frac{1}{T} \right)$$



In the absence of E field, dipoles are randomly oriented. So net polarization is zero.

with the application of field all  
the dipoles aligned parallel  
to field, giving rise to non zero  
polarization.



### Space charge Polarization:-

This type of polarization is the result of lattice vacancies and impurity centers present in the material.

In dielectrics some free charge carriers are also available that can migrate from one end to the another end of dielectric. Free charge carrier migration through the dielectric under the influence of  $E$  field can be obstructed by lattice vacancy and impurity centers. These charge carriers may be trapped by these impurities. This will result in local accumulation.

(37)

of charges inside dielectric. Its image charge which is opposite in polarity will deposit on electrodes. Hence there is a formation of dipole and contribution of a polarization called space charge polarization.

- material having lattice vacancies are

Material known as multiphase materials total polarization for these materials is given by

$$P_T = P_e + P_i + P_o + P_s -$$

In case of single phase material.

$$P_T = P_e + P_i + P_o$$

\* Internal fields in Solids / Liquids :-

In gaseous dielectric internal field is equal to external field (as far as molecular density is reasonably low)

In case of solid & liquids, molecules or atoms are so close together that field experienced by them is due to 2 factors.

i) because of applied E-field.

e) because of polarization inside dielectric material.

the internal field is given by: (3e)

$$E_i = E + \frac{\gamma P}{\epsilon_0}$$

where  $E$  = external field

$P$  = polarization

$\gamma$  = internal field constant

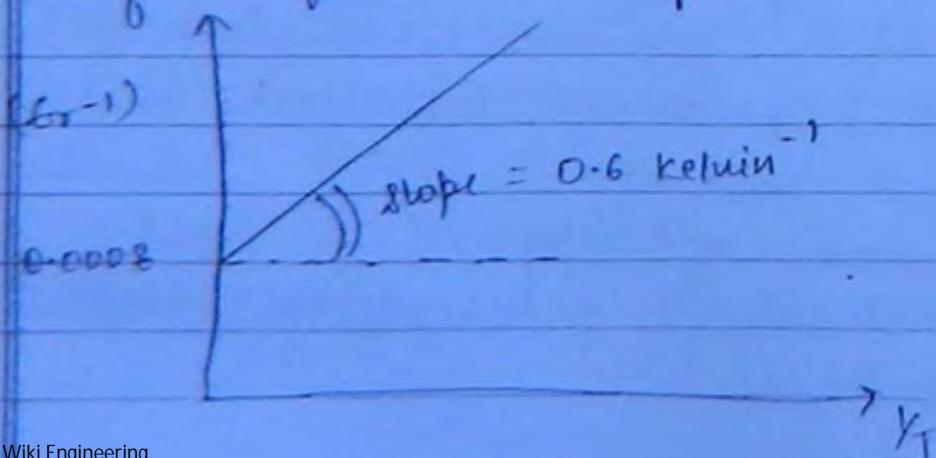
$\gamma$  is a unitless quantity, and its value depends on crystal structure

for cubic crystal structure:

$$\gamma = \gamma_3$$

$$E_i = E + \frac{P}{3\epsilon_0} \rightarrow \text{Lorentz field.}$$

Q The variation of the dielectric constant of  $C_6H_5N$  as a fn of temp are plotted in the figure calculate permanent dipole moment of molecule if no. of molecules per  $m^3$  is  $2.5 \times 10^{25}$ .



Sol'

$$N(\alpha_e + \alpha_i) = 0.0008$$

(39)

$$\frac{N P_p p_p^2}{3K\epsilon_0} = 0.6 \text{ Kelvin}^{-1}$$

$$N = 2.5 \times 10^{25}$$

$$P_p^2 = \frac{0.6 \times 3 \times 1.38 \times 10^{-23}}{2.5 \times 10^{25}} \times 8.85 \times 10^{-12}$$

$$P_p = 2.97 \times 10^{-30} \text{ C-m}$$

\* Classification of dielectric on the basis of their dielectric behaviour:-

- 1. Elemental dielectric solid
- 2. Ionic non polar solid
- 3. Polar solids.

### 1. Elemental Dielectric Solids :-

- These are the solids which posses only electronic polarization.
- These solids consist of only single type of atom. ex: diamond, sulphur, Si, Ge.
- Total polarization of solids can be given by

$$P = N \alpha_e E_i$$

$$\& E_i = E + \frac{\rho}{\epsilon_0}$$

## Measurement of dielectric constants

of solid:-

As we know,

(50)

$$\rho = N \alpha e E_i \quad \text{--- (1)}$$

$$\delta E_i = E + \frac{\gamma}{\epsilon_0} \rho.$$

F

from (1)

$$\rho = N \alpha e \left[ E + \frac{\gamma}{\epsilon_0} \rho \right]$$

$$\Rightarrow \rho \left[ 1 - \frac{N \alpha e \gamma}{\epsilon_0} \right] = N \alpha e E$$

$$\Rightarrow \rho = \frac{N \alpha e}{1 - \frac{N \alpha e \gamma}{\epsilon_0}} \cdot E$$

Also,

$$\rho = \epsilon_0 \chi_e E$$

$$\Rightarrow \epsilon_0 \chi_e E = \frac{N \alpha e}{1 - \frac{N \alpha e \gamma}{\epsilon_0}} E$$

$$\Rightarrow \epsilon_r - 1 = \frac{N \alpha e / \epsilon_0}{1 - \frac{N \alpha e \cdot \gamma}{\epsilon_0}}$$

$$\Rightarrow \boxed{\epsilon_r = \frac{1 - (\gamma - 1) N \alpha e / \epsilon_0}{1 - \gamma \frac{N \alpha e}{\epsilon_0}}}$$

- CM eq<sup>n</sup> (Clausius - Mossotti eq<sup>n</sup>)
- This eq<sup>n</sup> is applicable only for materials having cubical structure (having Lorentz field).

As we know

(41)

$$\gamma = \gamma_3$$

$$P = Nde E_i$$

$$E_i = E + \frac{P}{3\epsilon_0}$$

$$\epsilon_{r-1} = \frac{Nde/\epsilon_0}{1 - \frac{Nde}{3\epsilon_0}} \quad (1)$$

$$\epsilon_{r+2} = \frac{Nde/\epsilon_0}{1 - \frac{Nde}{3\epsilon_0}} + 3$$

$$\epsilon_{r+2} = \frac{3}{1 - \frac{Nde}{3\epsilon_0}} \quad (2)$$

from (1) & (2)

$$\boxed{\frac{\epsilon_{r-1}}{\epsilon_{r+2}} = \frac{Nde}{3\epsilon_0}} \rightarrow \text{CM eq<sup>n</sup>}$$

\* Maxwell's Relation:

Relation b/w Refractive index and relative permittivity of dielectric material

$$\eta = \frac{c}{v}$$

$$\eta = \frac{c}{v} = \frac{1}{\mu_0 \epsilon_0} \cdot \frac{1}{\left(\frac{1}{\mu_0 \epsilon_0}\right)}$$

$$= \frac{1}{\mu_0 \epsilon_0 \epsilon_r} \quad (42)$$

$$\eta = \frac{1}{\mu_0 \epsilon_0 \epsilon_r} \quad (1)$$

for dielectrics:

$$\epsilon_r \approx 1$$

from eq (1)

$$\boxed{\epsilon_r = \eta^2}$$

Debye's generalization of CM eq<sup>n</sup>:  
It is applicable for gaseous dielectrics.

for gaseous dielectrics.

$$\boxed{N = \frac{N_A \cdot P}{M}}$$

where  $N_A$  = Avagadro no.

$$N_A = 6.023 \times 10^{23}$$

CM eq<sup>n</sup>:

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

$$\frac{\epsilon_r - 1}{\epsilon_r + 2} = \left( \frac{N_A \cdot P}{M} \right) \cdot \frac{\alpha_e}{360}$$

(43)

$$\Rightarrow \boxed{\frac{N_A \cdot \alpha_e}{360} = \frac{\epsilon_r - 1}{\epsilon_r + 2} \cdot \frac{M}{P} \approx \kappa}$$

Lorentz-Lorentz eq<sup>n</sup>  
Acc. to Maxwell's relation.

$$\epsilon_r = n^2$$

then

$$\boxed{\frac{N_A \cdot \alpha_e}{360} = \frac{n^2 - 1}{n^2 + 2} \cdot \frac{M}{P}}$$

This eq<sup>n</sup> is applicable only for gaseous dielectric having electronic polarization  
ex: Rare gases

Tonic non-polar solids :-

These solid posses electronic as well as ionic polarization.

They don't have permanent dipole.

These solids consist of more than one type of atoms ex. alkali halides & total polarization

$$P = P_e + P_i$$

$$\boxed{P = N(\alpha_e + \alpha_i) E}$$

### 3. Polar solids:

(44)

These solid possess electronic, ionic as well as orientational polarization

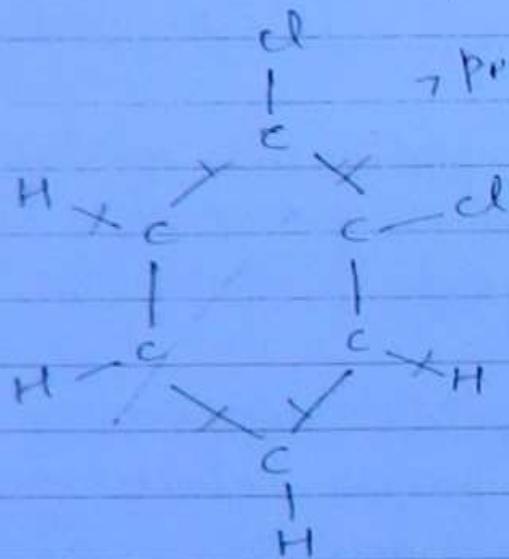
They carry permanent dipole moment

These are the solid having asymmetrical nature of molecule

These solid consist of dissimilar atom having partial ionic bond.

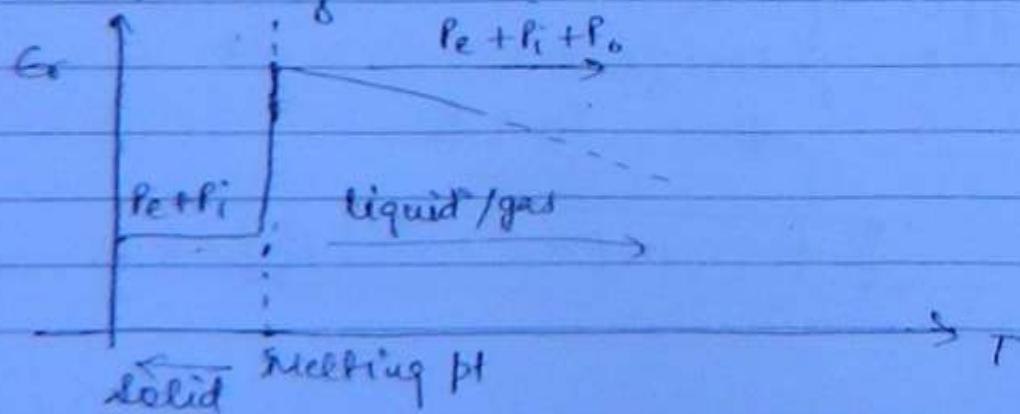
Ex: p-Nitro benzene, ortho & meta dichlorobenzene

### ortho dichlorobenzene



### Some Important points:-

Nitrobenzene ( $C_6H_5N$ )



Polar solids contain permanent dipole but these dipoles are present in solid state (S) and can no longer be aligned in the field direction. Thus in case of polar solids all the electronic and ionic polarization can be measured.

In case of liquids/gases  $\epsilon_r$  is with ↑ in temp<sup>r</sup> due to the fact that orientational polarization decreases with temp<sup>r</sup>.

In solids  $\epsilon_r$  is independent of temp<sup>r</sup> whereas it ↓ with temp<sup>r</sup> in case of liquids & gases.

Classification of dielectric on the basis of their dielectric behaviour in E-field:-

- Piezo electric material
- Pyro electric material
- Ferro - electric → charge generation by applied E-field & converse.
- Anti- ferro electric

i) Piezoelectric Material :-

charge generation with applied mechanical field & converse.

Pyro electric: charge generation with applied thermal field & converse.

Piezoelectric Material :- Some materials get polarized when they are subject a mechanical stress. Such materials are called piezo electric material & this property of material is called piezoelectricity. When these material are subjected to an electric field, material gets strain.

Produce strain is proportional to applied electric field.

There are 2 effects in piezoelectricity

• Direct effect

• Inverse effect

Direct effect: charge generation by applied mechanical stress.

Application:- microphone

Inverse effect: Generation of strain by applied E-field.

Application - Quartz watches

ex: Quartz , BaTiO<sub>3</sub> (Barium titanate)

PbTiO<sub>3</sub> (Lead titanate), PbZrO<sub>3</sub> (Lead

Zirconate) , Rochelle salt,

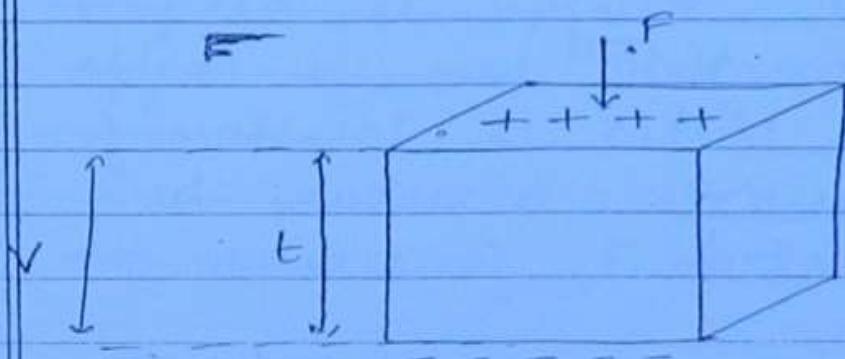
ADP (Ammonium dihydrogen phosphate)

KDP (Potassium " )

PZT (Lead zirconate titanate),  
Lithium sulphate.

(47)

- \* Expression for voltage sensitivity of piezo-electric material.



Produced charge when mechanical force 'F' is applied on material

$$\Rightarrow Q \propto F$$
$$\Rightarrow Q = dF$$

charge sensitivity  
(unit: C/N)

$$\Rightarrow CV = dF$$

$$\Rightarrow V = \frac{dF}{C}$$

$$= \frac{dF}{(\epsilon A/t)}$$

$$V = \left( \frac{F}{A} \right) \left( \frac{t}{\epsilon} \right) \cdot t$$

$$V = P \cdot g \cdot t$$

(48)

P → pressure / mech. stress

where  $g$  = voltage sensitivity [Vm/N]

$$= \frac{V}{P \cdot t}$$

$$= \frac{V \cdot A}{F \cdot t}$$

Ex Calculate the voltage generated across a piezoelectric material of thickness 1 cm when a mechanical stress of  $10 \text{ N/m}^2$  is applied.  
[ given,  $g = 2.3 \times 10^3 \text{ Vm/N}$  ]

$$P = 10 \text{ N/m}^2$$

$$g = 2.3 \times 10^3 \text{ Vm/N}$$

$$t = 1 \times 10^{-2} \text{ m}$$

$$V = P g t$$

$$= 2300 \text{ V}$$

- \* Application of piezoelectric
- ④ Resonators
- ② Filters

- ③ Ultrasonic flow deflectors  
 ④ Accelerometers.

(4)

\* Electrostriction :-

Some materials gets strain when an E-field is applied. but converse effect is not observed. This property of material is called electrostriction and produced strain is proportional to square of E-field

$$\text{strain} \propto E^2$$

② Pyro electric materials :-

charge produced with change in temperature is called pyroelectricity these materials posses spontaneous polarization.

The direction of polarization cannot be reversed by reversing the dir<sup>n</sup> of E-field.

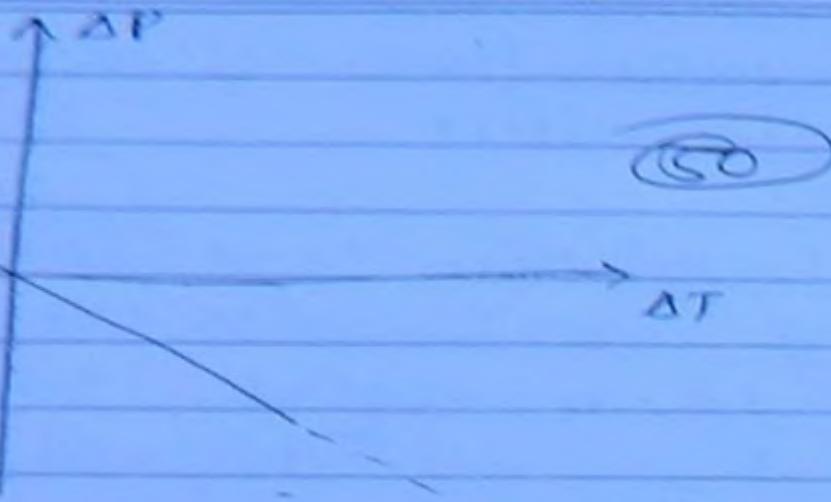
As the temp<sup>r</sup> is increased due to thermal agitation of dipoles polarization decreases.

$$\rightarrow \text{As } T \uparrow \Rightarrow P \downarrow$$

$$\text{or As } T \downarrow \Rightarrow P \uparrow$$

$$[\Delta P = \lambda \Delta T]$$

$\lambda \rightarrow$  pyroelectric coefficient (-ve)



ex: BaTiO<sub>3</sub>, Tourmaline

The change in temp° modifies the positions of atoms in the crystal structure such that polarization of material changes. This "change gives rise to a voltage across the crystal. If the temp° stage constant at its new value the pyroelectric voltage gradually disappears due to leakage current. In pyroelectricity, the whole crystal is change from one temp° to another and the result is temporary voltage across the crystal.

In thermo electricity, one side of material is kept at one temp° & the other side is at different temp° & the result is permanent voltage across the crystal

Spontaneous Polarization: 51  
 Certain dielectric exhibit non-zero polarization even in the absence of E-field. This residual polarization is called spontaneous polarization.

As we know,

$$P = N\alpha E_i \quad \dots \quad (1)$$

$$\& \quad E_i = \epsilon + \frac{\gamma P}{\epsilon_0}$$

from (1)

$$P = N\alpha \left[ \epsilon + \frac{\gamma P}{\epsilon_0} \right]$$

$$P = \frac{N\alpha}{1 - N\alpha \frac{\gamma}{\epsilon_0}} \epsilon \quad \dots \quad (2)$$

for spontaneous polarization

$$\text{if } \epsilon = 0 \Rightarrow P \neq 0$$

to achieve above condition, value of denominator of eq.(2) should be zero.  
 i.e

$$1 - \frac{N\alpha\gamma}{\epsilon_0} = 0$$

$$\Rightarrow \left| \frac{N\alpha\gamma}{\epsilon_0} = 1 \right|$$

→ Spontaneous polarization is possible only when

$$\frac{N\alpha Y}{\epsilon_0} = 1$$

(52)

Open Loop system :

E

$$A = N\alpha$$

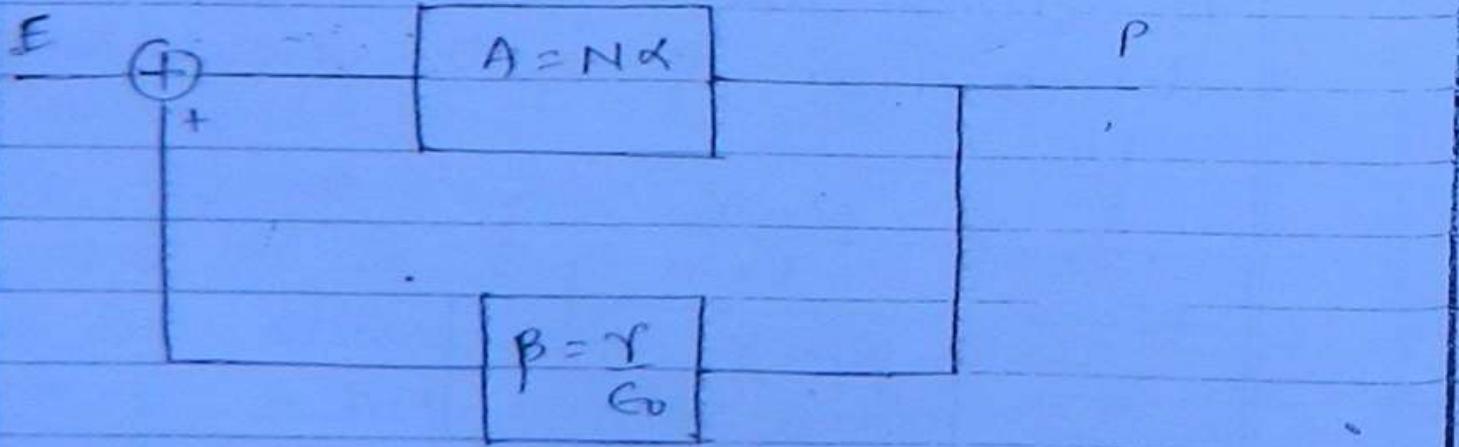
$$P = N\alpha E$$

In case of gaseous dielectric material behaves as an O/L system with

$$\text{O/L gain} = A = N\alpha$$

Closed Loop system :

$$P = \frac{N\alpha}{1 - \frac{N\alpha Y}{\epsilon_0}} E$$



In case of solid & liquid material behaves as a C/L system with the feedback, having

$$\Lambda = N\alpha$$

(SB)

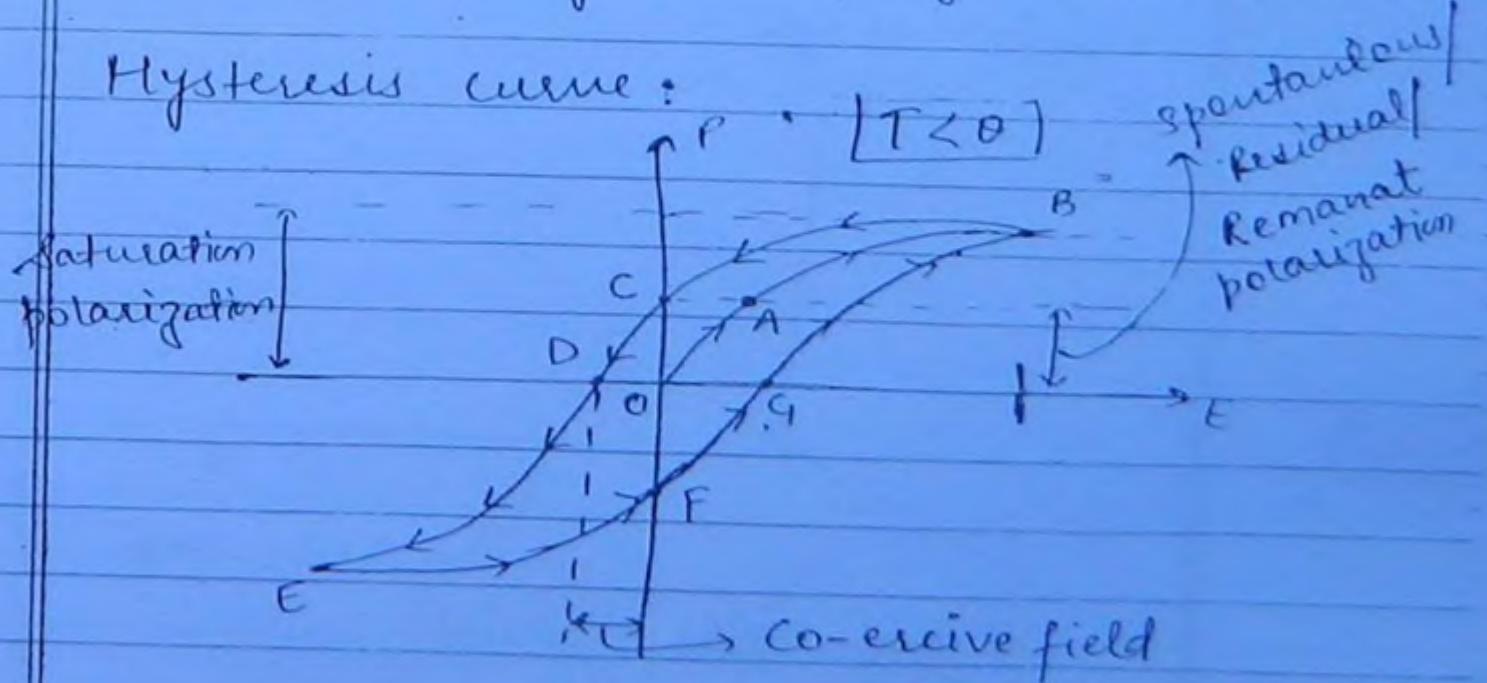
$$\text{f/b factor } \beta = \frac{r}{C_0}$$

(3)

Ferroelectric material :-

- Ferroelectric material exhibit the phenomenon of hysteresis curve
- These material posses spontaneous polarization ( non zero polarization even in the absence of E-field ).
- the dir<sup>n</sup> of polarization can be reversed by reversing the dir<sup>n</sup> of E-field.
- These materials remain ferroelectric upto a critical temp<sup>r</sup> called curie temp<sup>r</sup> and above this temp<sup>r</sup> these material start behaving like piezo electric materials

Hysteresis curve :

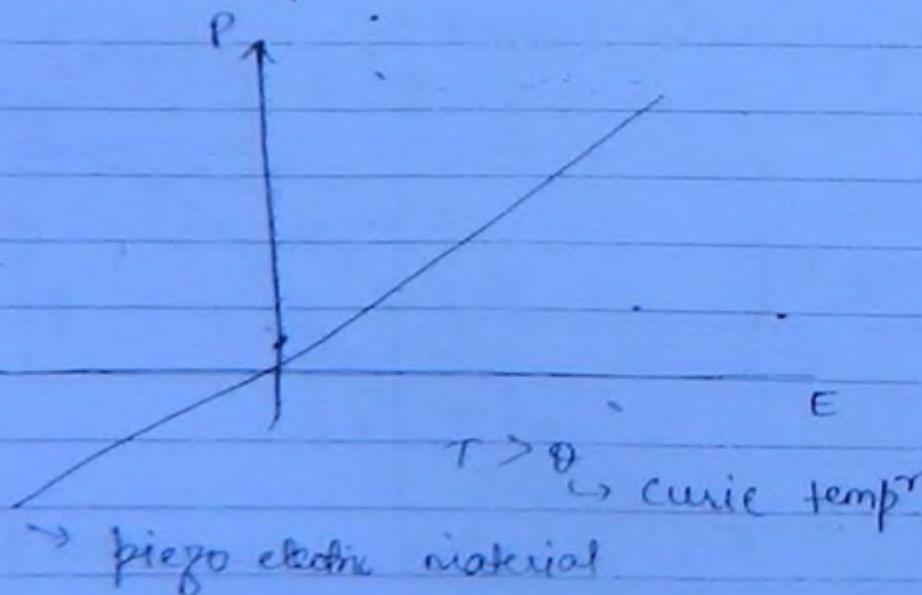


when a ferroelectric material is subjected to an external E-field, the material follows the path OAB in the hysteresis curve. The material remains polarized even if the external field is reduced to zero. This residual value of polarization is called spontaneous / residual / remanent polarization.

To reduce the residual polarization to zero an E-field is required to be applied in opposite direction. This field is called co-ercive field.

Above Curie Temp<sup>\*</sup>:

When temp<sup>\*</sup> is  $T$ , the area of hysteresis loop  $\downarrow$  and it merges into a straight line above Curie temp<sup>\*</sup>.



Above curie temp<sup>r</sup> polarization is proportional to applied E-field and relationship is governed by curie-weiss law.

(58)

Curie Weiss Law :-

Polarization of piezo electric material can be assumed to be orientational polarization

$$P = P_0 = \frac{N p_p^2}{3KT} E_i \quad \dots \quad (1)$$

Also,

$$E_i = E + \frac{\gamma}{\epsilon_0} \cdot P$$

from eq. (1)

$$P = \frac{N p_p^2}{3KT} \left[ E + \frac{\gamma}{\epsilon_0} P \right]$$

$$\Rightarrow P \left[ 1 - \frac{N p_p^2}{3KT} \cdot \frac{\gamma}{\epsilon_0} \right] = \frac{N p_p^2 \cdot E}{3KT}$$

$$\Rightarrow P = \frac{N p_p^2}{3KT} \cdot E$$

$$1 - \frac{N p_p^2}{3KT} \cdot \frac{\gamma}{\epsilon_0}$$

$$P = \frac{N p_p^2}{3K} \cdot E$$

$$1 - \frac{N p_p^2}{3K} \cdot \frac{\gamma}{\epsilon_0}$$

$$\boxed{P = \frac{C \epsilon_0 \cdot E}{T - \Theta}} \quad \textcircled{2}$$

curie-weiss law 56

As we know,

$$P = \epsilon_0 X_e E \quad \textcircled{3}$$

from 2 & 3

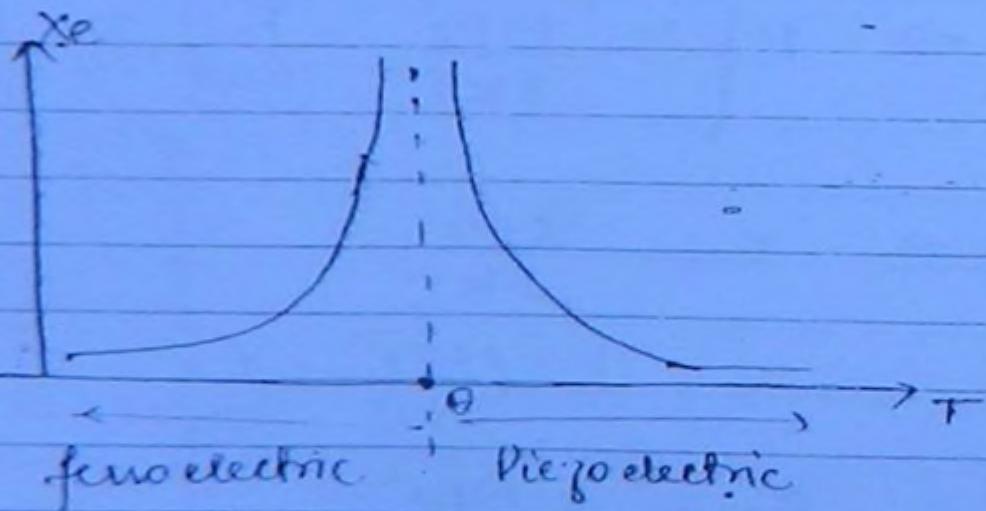
$$\boxed{X_e = \frac{C}{T - \Theta}}$$

where  $C = \text{curie const.} = \frac{N \rho_p^2}{3 K \epsilon_0}$

$\Theta = \text{curie temp}^* = \frac{N \rho_p^2 \cdot \gamma}{3 K \epsilon_0}$

$\gamma$  = internal field constant

$$= \frac{\Theta}{C}$$



Susceptibility of ferroelectric material: ↑ with temp<sup>r</sup> and it ↓ with temp<sup>r</sup> in case of piezoelectric materials

(57)

ex: of ferroelectric materials:-

- ✓ 1. Rochelle Salt
- ✓ 2. BaTiO<sub>3</sub>
- 3. PbTiO<sub>3</sub>
- ✓ 4. KDP
- 5. Alums
- 6. Sodium Nitrate

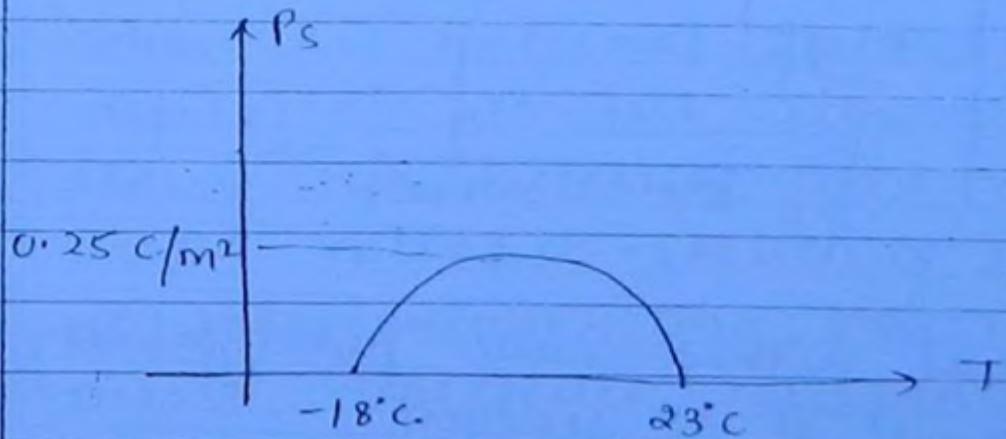
\* Rochelle Salt :-

This is first ever discovered ferroelectric material.

It has unique property of 2 curie temp<sup>r</sup>

$$\theta_1 = -18^\circ\text{C}$$

$$\theta_2 = 23^\circ\text{C}$$



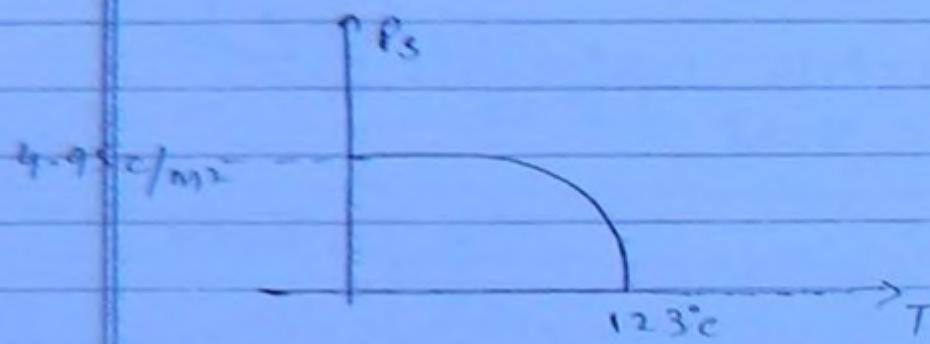
$$P_{s\max} = 0.25 \text{ C/m}^2$$

KDP (Potassium Dihydrogen phosphate):

$$\Theta = 123^\circ\text{C}$$

$$P_{s\max} = 4.95 \text{ C/m}^2$$

(58)

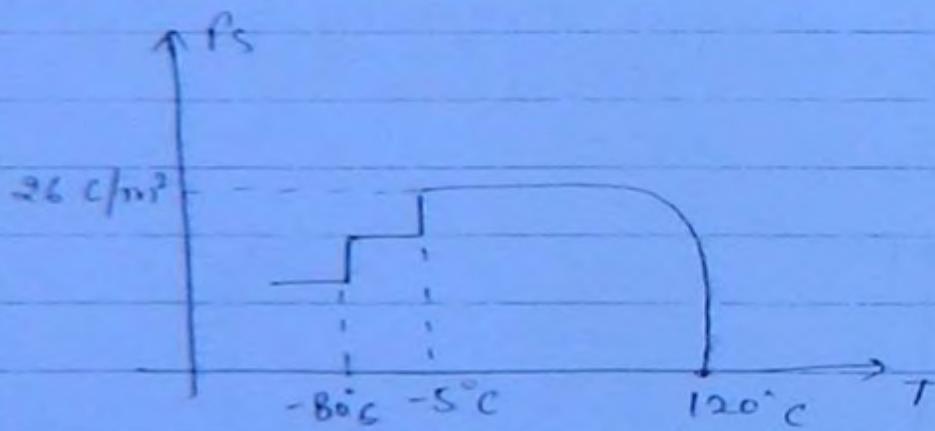


BaTiO<sub>3</sub> :-

it is best known ferro-electric material

$$\text{Curie temp}^\circ\Theta = 120^\circ\text{C}$$

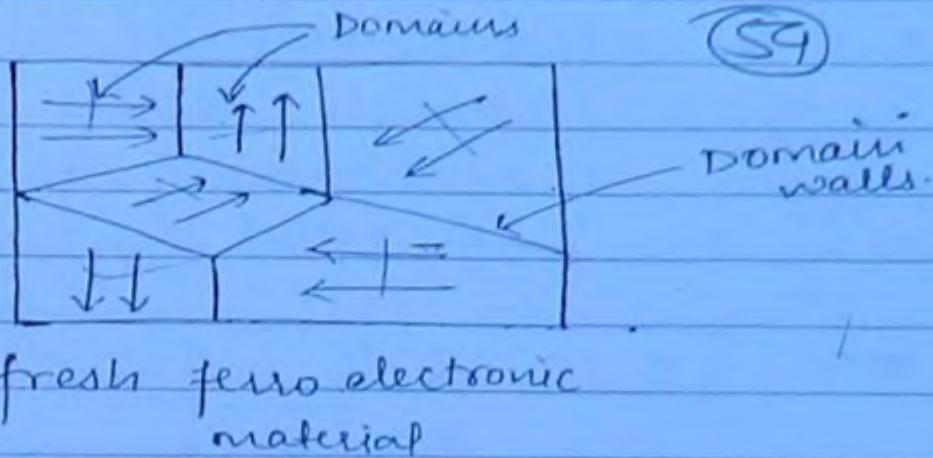
$$P_{s\max} = 26 \text{ C/m}^2$$



It has highest ionic polarizability because of 2 reason.

- i) Titanium ion have charge of +4 unit.
- ii) It can be displaced over a large distance.

## Ferroelectric domain :- (conv.)



each ferroelectric material is divided into no. of small regions. each region is spontaneously polarized with uniform dir<sup>n</sup> of polarization (each domain is magnetically saturated).

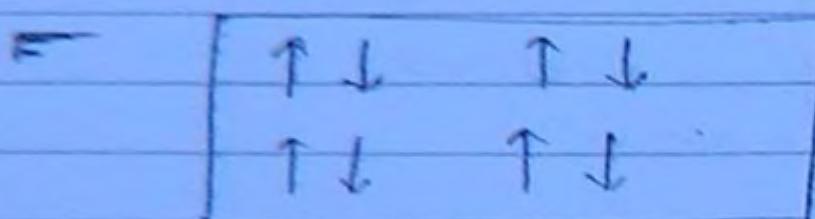
the dir<sup>n</sup> of polarization varies from one region to another region. these region are called ferroelectric domain. the boundary separating ferroelectric domain are called domain wall.

when an external field is applied, dipoles of all the regions get aligned along the external field and domain wall collapse resulting in increase in polarization (OAB path in hysteresis curve represents collapsing of domain walls and growth of single domain having all the dipole in same dir<sup>n</sup>)

#### ④ Anti ferroelectric material :-

- In these materials dipoles are aligned in antiparallel dir<sup>n</sup>. but they are ~~not~~ equal

(60)

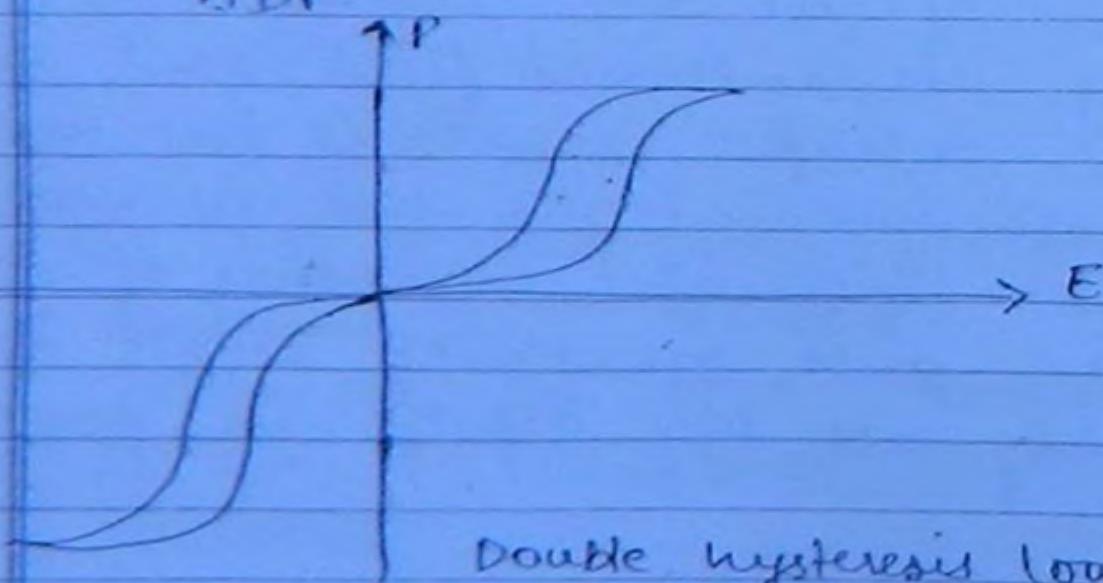


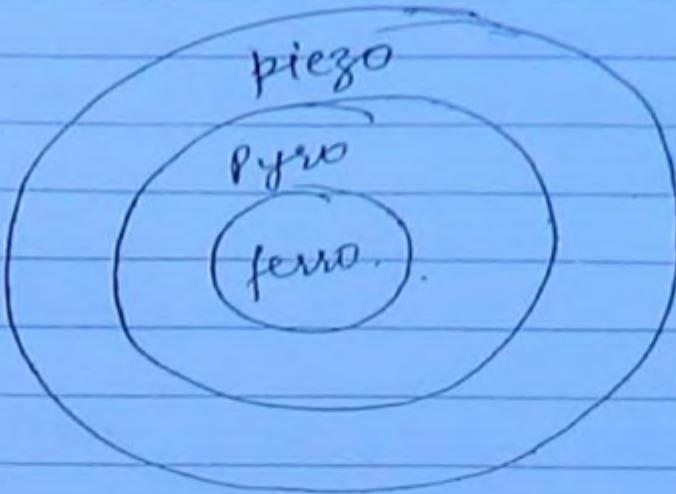
These material posses zero spontaneous polarization.

These materials are anti-ferroelectric upto a critical temp<sup>r</sup> called curie temp<sup>r</sup>. and above this temp<sup>r</sup> these materials start behaving like piezoelectric materials.

Ex: Lead Zirconate ( $PbZrO_3$ )  
Sodium Niobate

ADP





(Q)

- All ferro are piezo & pyro
- All pyro electric materials are piezo electric.

\* Para electric Materials :-

- these materials contain permanent dipoles.
- due to random arrangement of dipole, spontaneous polarization is zero.
- Under the influence of E-field, all the dipoles get aligned in the field dir & result is the non-zero polarization.

Ex. Ceramic materials

Consider the following statement related to piezoelectric material.

1. Mechanical stress apply to the material produces electronic polarization.
2. An E-field applied to the material

produces strain in it.

3. All piezo electric materials are also ferroelectric.

Ans

1 & 2 .

(62)

Q. consider ~~the~~ following statement :

In a ferroelectric material.

1. All domains are lined up in the direction of E-field giving rise to saturation.

2. If the field is reduced to zero, many domains remained aligned

3. the remanent polarization can be eliminated only if the Material is heated above the curie temp.

- which are correct.

sol

1 & 2 .

Q Piezo electricity is the reverse effect of.

a) Electro luminescence

b) Electro striction

c) Peltier effect

d) Hall effect

|

Q In a solid or liquid dielectric with externally apply E-field.

as the interatomic distance ↑ the internal field  $E_i$ :

- a) Increases
- b) Decreases
- c) Remains unaltered
- d) Increases or decreases based on temp.

(63)

Sol:

$$E_i = E + \frac{\gamma}{\epsilon_0} P$$

$$= E + \frac{\gamma}{\epsilon_0} (N \alpha E_i)$$

$$\Rightarrow E_i = \frac{E}{\left(1 - \frac{\gamma \alpha N}{\epsilon_0}\right)}$$

(b)

Q A long narrow rod has an atomic density  $5 \times 10^{28}$  atoms/m<sup>3</sup>. each atom has a polarizability of  $10^{-40} F \cdot m^2$  find  $E_i$  when an axial field of 1 V/m is applied.

$$\gamma = V_3$$

Sol:  $E = 1 \text{ V/m}$

$$E_i = 1 + \frac{1}{3 \times 8.85 \times 10^{-12}}$$

$$E_i = \frac{1}{\left(1 - \frac{10^{12} \times 10^{-40} \times 5 \times 10^{28}}{3 \times 8.85}\right)}$$

$$E_i = 1.23 \text{ V/m}$$

8 A dielectric material contains  $2 \times 10^{19}$  polar molecule/m<sup>3</sup>. each of dipole moment  $1.8 \times 10^{-27}$  C-m. (64)  
 Assuming that all the dipoles are aligned in the dir<sup>n</sup> of E-field.  
 $E = 10^5$  V/m.

Find  $\rho$  &  $\epsilon_r$ .

~~Defn.~~

$$E = 10^5 \text{ V/m}$$

$$\rho_p = 1.8 \times 10^{-27}$$

$$N = 2 \times 10^{19}$$

$$\begin{aligned} \rho &= N\rho_p \\ &= 1.8 \times 10^{-27} \times 2 \times 10^{19} \\ &= 3.6 \times 10^{-8} \text{ C/m}^2 \end{aligned}$$

$$\epsilon_{r0} \rho = \epsilon_0 (\epsilon_r - 1) E$$

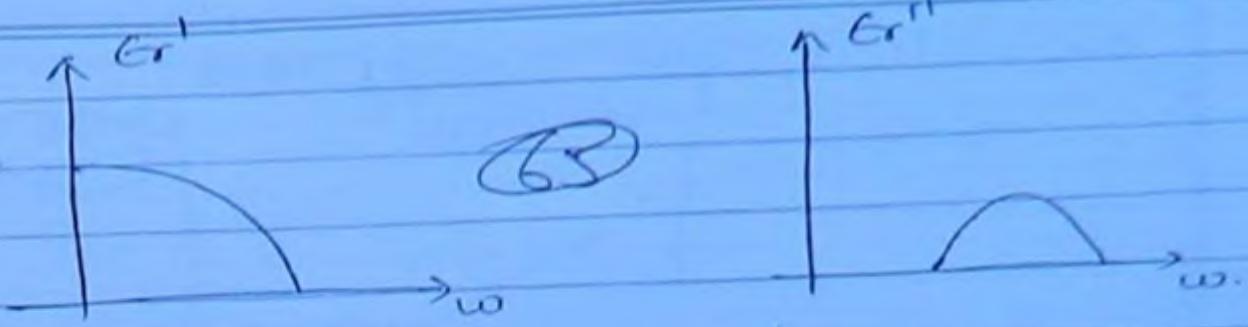
$$\epsilon_r = 1 + \frac{\rho}{\epsilon_0 E}$$

$$\epsilon_r = 1.04$$

\* Dielectrics in AC field :-

Dielectric constant with was real for static field, breaks into real & imag. part when ac field is applied.

$$\epsilon_r = \epsilon'_r - j\epsilon''_r$$



Real part of dielectric constant  $\epsilon_r'$  with freq.

Imag. part of dielectric constant  $\epsilon_r''$ , attains a max. value and then ~~decreases~~ with freq".

At lower freq. real part is dominating and at higher freq" imag. part of dielectric constant is dominating

$\epsilon_r$  of solid dielectrics in the ac field is max. at power freq (upto 100Hz) and  $\rightarrow$  unity at freq. in ~~upto~~ ultra violet range.

#### \* Dielectric Losses :-

the absorption of electrical energy by a dielectric material subjected to an ac field is known as dielectric losses. the result is dissipation of electrical energy in the form of heat it occurs due to  $\alpha$  reasons.

- 1) Oscillation of losses
- 2) continuous change in orientation of dipole.

Derivation for energy loss:

(Q)

$E_r$

$$E(t) = E_0 \cos \omega t$$

|

F

$$P = \epsilon E(t)$$

$$= \epsilon E_0 \cos \omega t$$

$$= \operatorname{Re} [\epsilon E_0 \cdot j \omega e^{j\omega t}]$$

J = current density.

$$= \frac{d(P)}{dt}$$

$$= \operatorname{Re} [\epsilon E_0 \cdot j \omega e^{j\omega t}]$$

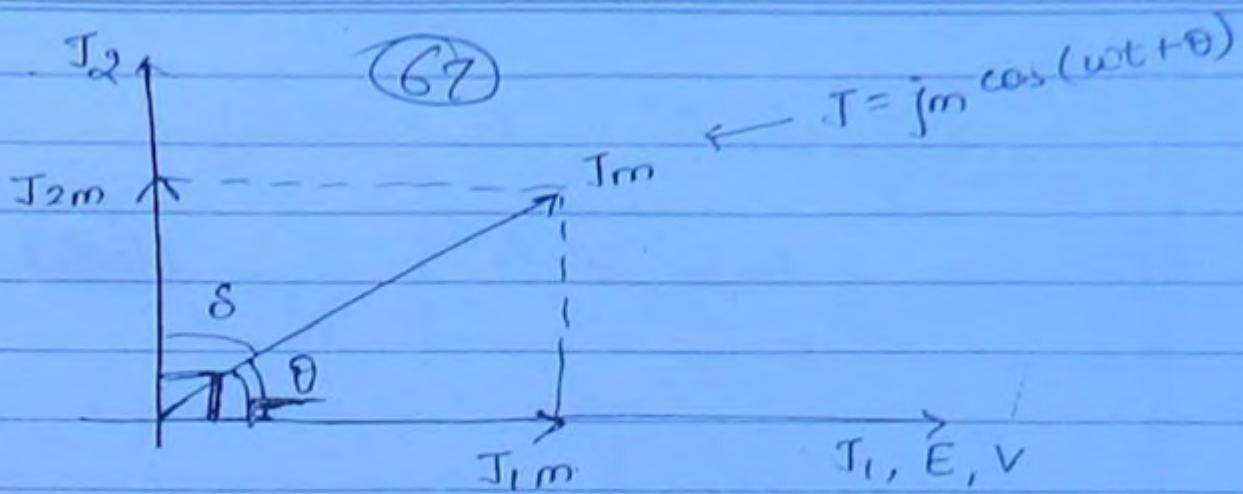
$$= \operatorname{Re} [E_0 E_0 \omega (\epsilon_r' - j \epsilon_r'') j \\ (\cos \omega t + j \sin \omega t)]$$

$$J = E_0 E_0 \omega [\epsilon_r'' \cos \omega t - \epsilon_r' \sin \omega t]$$

$$= \underbrace{E_0 E_0 \omega \epsilon_r'' \cos \omega t}_{J_1 = J_{1m} \cos \omega t} + \underbrace{E_0 E_0 \omega \epsilon_r'}_{\cos(\frac{\pi}{2} + \omega t)}$$

$$J_1 = J_{1m} \cos \omega t$$

$$J_2 = J_{2m} \cos\left(\frac{\pi}{2} + \omega t\right)$$



where  $\delta$  = loss angle

$$\tan \delta = \text{tangent loss} = \frac{J_{1m}}{J_{2m}}$$

$$= \frac{\epsilon_0 E_0 \omega \epsilon_r''}{\epsilon_0 E_0 \omega \epsilon_r'}$$

$$\boxed{\tan \delta = \frac{\epsilon_r''}{\epsilon_r'}}$$

$$\boxed{0.0001 \leq \tan \delta \leq 0.001} \rightarrow \text{obj}$$

$$\boxed{\text{loss factor} = \epsilon_r' \tan \delta \\ = \epsilon_r''}$$

Avg. power absorbed per unit volume  
in one cycle:

$$P \left( \frac{\text{watt}}{\text{m}^3} \right) = \frac{1}{2\pi} \int_0^{2\pi} J \cdot E(t) \cdot d(\omega t)$$

$$P = \frac{1}{2\pi} \int_0^{2\pi} E_0 \cos \omega t \epsilon_0 E_0 \omega \\ (\epsilon_r'' \cos \omega t - \epsilon_r' \sin \omega t) d(\omega t)$$

$$= \frac{1}{2\pi} \epsilon_0 \epsilon_r^2 \omega \cdot \delta'' \delta' \times \frac{1}{2}$$

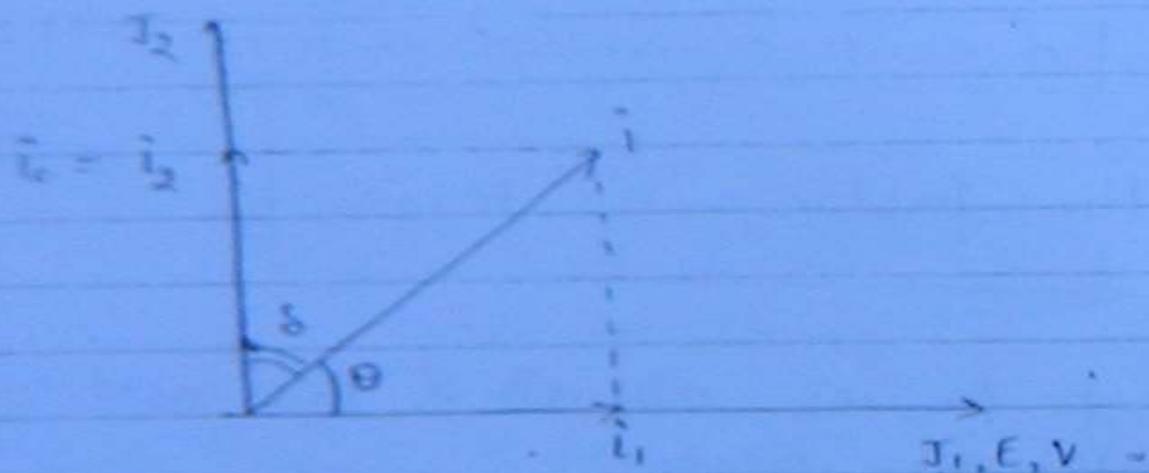
$$P = \frac{1}{2} \epsilon_0 \epsilon_r^2 \omega \delta''$$

(68)

$P \propto \epsilon_0^2$
$\propto \omega$
$\propto \delta''$

Dielectric loss is proportional to imag. part of dielectric constant

Dielectric loss using A.C. analysis:



Power loss:

$$\begin{aligned} P_L &= V_i I \cos \theta \\ &= V_i I \cos(90^\circ - \delta) \\ &= V_i I \sin \delta \end{aligned}$$

$$\cos \delta = \frac{i_2}{i} \Rightarrow i = \frac{i_2}{\cos \delta}$$

$$P_L = V \cdot \tilde{i}_L \cdot \sin \delta$$

$$= V \tilde{i}_L \tan \delta$$

(69)

$$\left[ \tilde{i}_c = C \frac{dv}{dt} \Rightarrow \tilde{i}_c(\omega) = C j \omega v(\omega) \right]$$

$$P_L = V \tilde{i}_c \tan \delta$$

$$P_L = V \cdot \frac{V}{X_C} \tan \delta$$

$$= V^2 \omega C \tan \delta$$

$$\boxed{P_L = V^2 2\pi f C \tan \delta} \text{ watt}$$

$$P_L = (E_0 d)^2 2\pi f \frac{\epsilon A}{d} \tan \delta$$

, volume

$$= E_0^2 2\pi f \epsilon (A/d) \tan \delta$$

,  $\text{v/m}$

$$W (\text{watt/m}^3) = \frac{P_L}{Ad} = E_0^2 2\pi f \epsilon_0 \epsilon_r \tan \delta$$

,  $\text{v/cm}$

$$W (\text{watt/cm}^3) = \frac{E_0^2 f \cdot \epsilon_r \tan \delta}{1.8 \times 10^{12}}$$

B. A solid specimen of dielectric has relative permittivity  $\epsilon_r = 4.2$  and loss tangent  $\tan \delta = 0.001$  at 50 Hz freq. If it is subjected to an electric field of 50 KV/cm, what is the heat

generated in the specimen due to dielectric loss.

- (a)  $291 \text{ W/cm}^3$   
(b)  $5.82 \text{ MW/cm}^3$   
(c)  $19.5 \text{ W/cm}^3$   
(d)  $0.291 \text{ MW/cm}^3$ .

(d)

Sol<sup>n</sup>  $W = \frac{(50)^2 \times 50 \times 4\pi \times 0.001}{1.8 \times 10^{12}}$

$$W = 0.291 \text{ MW/cm}^3$$

~~Obj~~ Equation governing motion of  $e^-$  in an "ac field".

$$m \frac{d^2x}{dt^2} + 2b \frac{dx}{dt} + ax = -eE_0 \cos \omega t$$

where  $m$  represents mass of  $e^-$  cloud.

$2b$  = damping constant

$a$  = force or spring const.

$E_0 \cos \omega t$  = ac field.

$$\omega_0 = \text{natural freq} = \sqrt{\frac{a}{m}}$$

Q1

## Effect of frequency on Polarization:

(Ans)

- Interfacial or space charge polarization is effective upto power frequencies (upto 100 Hz)
- Orientational polarization is effective upto radio freq. (upto  $10^6$  -  $10^{10}$  Hz)
- Ionic polarization is effective upto Infrared freq. (upto  $10^{14}$  Hz).
- Electronic polarization is effective upto visible range (upto  $5 \times 10^{14}$  Hz)

Q

Consider the following statement regarding an insulating material connected to ac voltage

1. the dielectric constant  $\epsilon_r$  with freq.
  2. the dielectric const.  $\epsilon_0$  with freq.
  3. Atomic polarization  $\alpha$  with freq.
- which of these statement are correct?

Soln

Q

Consider the following statement :

The dielectric const of an insulator depends on -

1. Applied voltage
2. freq. of ac field
3. temp.
4. Max<sup>n</sup> current density in insulator

which of these statement are correct?

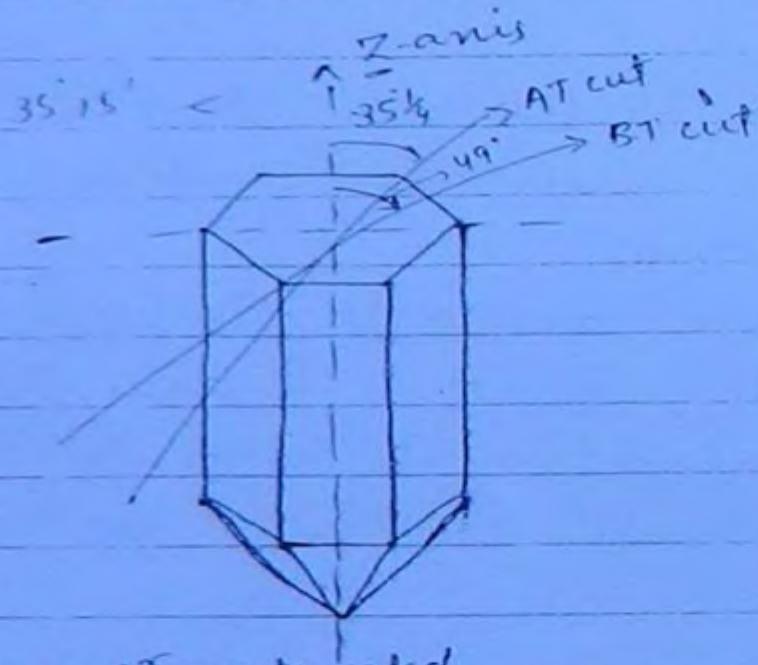
Q & 3.

(2)

Quartz:-

Quartz is a crystalline material  
its structure is silicate tetrahedral  
( $\text{SiO}_4$ ) .

It has a shape of hexagonal  
prism with pyramids attached  
at both the ends.



$\rightarrow$  temp° compensated  
AT-cut crystal plate:

A crystal plate making an angle  
of  $35^{\circ} 15'$  w.r.t Z-axis is called  
AT cut crystal plate.

It is most commonly used cut.

It has higher freq° stability over  
wide temp° range.

BT cut crystal plate:

(2)

A crystal plate making an angle of  $49^\circ$  w.r.t Z-axis.

It can be used for crystals with higher freq than AT.

Quality-factor range for Quartz crystal:

$$10^4 < Q < 10^6$$

Q In highly stable oscillator ckt, AT cut quartz crystal are generally employed. what is the reason for using this particular orientation.

1. Quartz crystal have a natural growth along this plane.

2. the corresponding quality factor is largest for this orientation.

3. AT cut crystals can be used over a wide freq range.

4. There is min freq variation wrt temp.

Q the resonance freq of a Quartz crystal oscillator shows least variation with temp when the orientation of crystal is

(a) X-cut

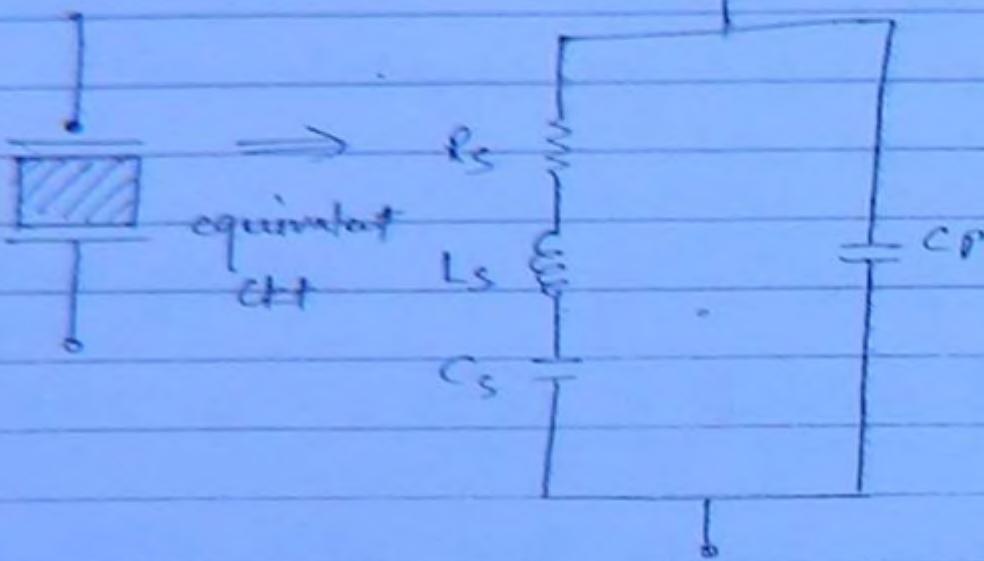
(b) Y-cut

(c) N.Y. cut

(d) AT-cut

\* Series & parallel resonating freq<sup>n</sup>  
of Quartz crystal:

(28)



where

$Rs$  = damping const

$L_s$  = mass of the crystal

$C_s$  = spring or force const.

$C_p$  = electrostatic capacitance b/w  
opposite surface of crystal.

$Z_s$  = Impedance of series arm.

$$Z_s = Rs + j \left( \omega L_s - \frac{1}{\omega C_s} \right)$$

$Z_p$  = impedance of shunt arm

$$Z_p = \frac{1}{j\omega C_p}$$

Total admittance :-

(24)

$$\gamma = \gamma_s + \gamma_p$$

$$\gamma = \frac{1}{R_s + j\left(\omega_{ls} - \frac{1}{\omega_{cs}}\right)} + j\omega_{cp}$$

$$\gamma = \frac{R_s - j\left(\omega_{ls} - \frac{1}{\omega_{cs}}\right)}{R_s^2 + \left(\omega_{ls} - \frac{1}{\omega_{cs}}\right)^2} + j\omega_{cp}$$

$$- \quad \gamma = \gamma_{real} + j\gamma_{imag.}$$

$$\gamma_{real} = \frac{R_s}{R_s^2 + \left(\omega_{ls} - \frac{1}{\omega_{cs}}\right)^2} \quad \text{--- (1)}$$

$$\gamma_{imag.} = \frac{\omega_{cp} - \left(\omega_{ls} - \frac{1}{\omega_{cs}}\right)}{R_s^2 + \left(\omega_{ls} - \frac{1}{\omega_{cs}}\right)^2} \quad \text{--- (2)}$$

for resonance:

$$\gamma_{imag.} = 0$$

$$\Rightarrow \frac{\omega_{cp} - \left(\omega_{ls} - \frac{1}{\omega_{cs}}\right)}{R_s^2 + \left(\omega_{ls} - \frac{1}{\omega_{cs}}\right)^2} = 0$$

$$\Rightarrow \omega_{cp} \left[ R_s^2 + \left( \omega_{ls} - \frac{1}{\omega_{cs}} \right)^2 \right] - \left( \omega_{ls} - \frac{1}{\omega_{cs}} \right) = 0$$

for higher amplitudes of oscillation:

$$R = 0$$

from eq. ② (11)

75

$$\left( \frac{\omega_{LS} - 1}{\omega_{CS}} \right) \left[ \omega_{CP} \left( \frac{\omega_{LS} - 1}{\omega_{CS}} \right) - 1 \right] = 0$$

$$\Rightarrow \frac{\omega_{LS} - 1}{\omega_{CS}} = 0 \quad \text{or} \quad \frac{1}{\omega_{CP}} \quad (11)$$

Series resonance:

$$Y_s = Y_{real} |_{max}$$

$$= \frac{R_s}{R_s^2 + \left( \frac{\omega_{LS} - 1}{\omega_{CS}} \right)^2} \Big|_{min}$$

$$\therefore \boxed{Y_s = \frac{1}{R_s}}$$

$$\Rightarrow \omega_s L_s - \frac{1}{\omega_s C_s} = 0$$

$$\boxed{\omega_s' = \frac{1}{\sqrt{C_s L_s}}}$$

for parallel resonance:

(78)

$$Y_p = Y_{\text{real}} \mid_{\text{min}}$$

$$Y_p = \frac{R_s}{R_s^2 + \left( \omega_{Ls} - \frac{1}{\omega_{Cs}} \right)^2} \mid_{\text{min}}$$

$\downarrow$   
 $Y_{\text{upper}}$

$$Y_p = \frac{R_s}{R_s^2 + \left( \frac{1}{\omega_p C_p} \right)^2}$$

$$\rightarrow \omega_p L_s = \frac{1}{\omega_p C_s} = \frac{1}{\omega_p C_p}$$

$$\omega_p = \frac{1}{\sqrt{L_s C'}}$$

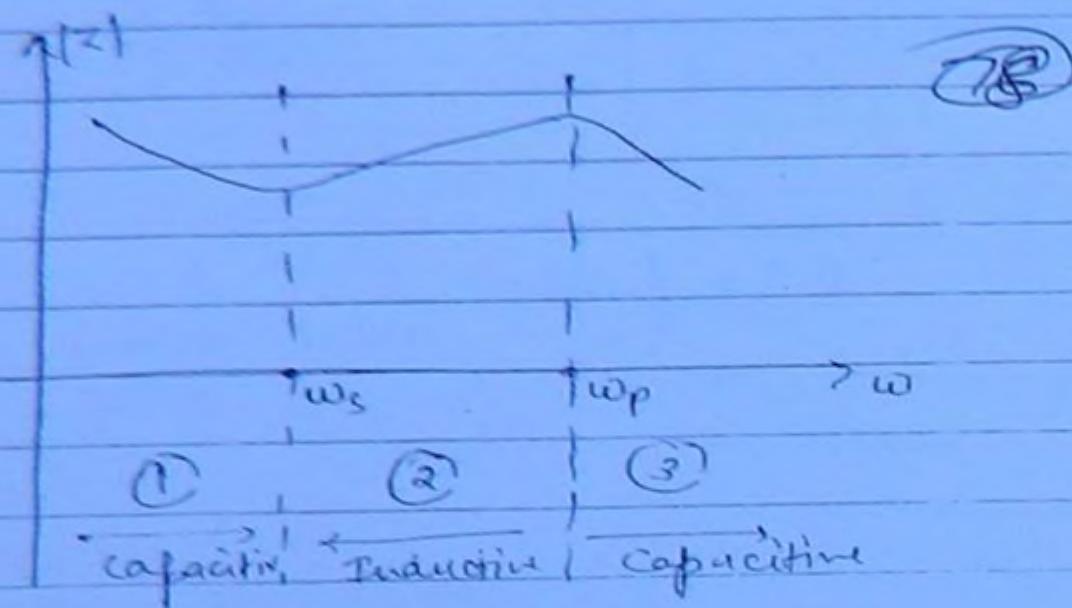
$$\text{where } C' = \frac{C_s C_p}{C_s + C_p}$$

Relation b/w series & parallel resonating freq: "w<sub>s</sub>" & "w<sub>p</sub>"

$$\omega_p = \omega_s \sqrt{1 + \frac{C_s}{C_p}}$$

w<sub>p</sub> > w<sub>s</sub>

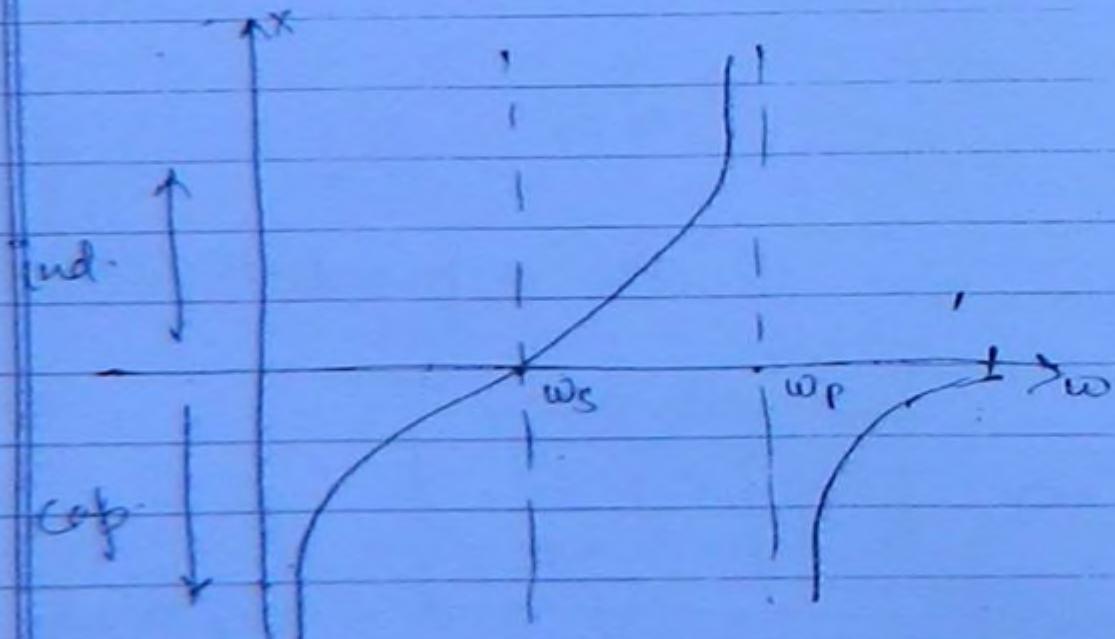
" $|Z|$ " Vs " $\omega$ ":



Conclusion:

1.  $\omega_p > \omega_s$
2. If  $\omega < \omega_s \Rightarrow$  crystal is capacitive
3. If  $\omega_s < \omega < \omega_p \Rightarrow$  " " Inductive
4. If  $\omega > \omega_p \Rightarrow$  " " Capacitive

"X" Vs " $\omega$ ": ( $R=0$ )



D A Quartz crystal have following characteristics:

- Series resonance = 200 kHz
- Impedance at series resonance =  $200\Omega$
- Parallel resonance =  $200 \cdot 25$  kHz
- Impedance at  $\Pi^{\text{rd}}$  resonance =  $40 \text{ M}\Omega$

(79)

Determine the component value?

def  $Z_s = R_s$

$$Y_p Z_p = 40 \text{ M}\Omega$$

$$\omega_s = 2\pi f_s \quad \omega_s = 200 \text{ kHz}$$

$$\omega_p = 200 \cdot 25 \text{ kHz}$$

$$Y_s = \frac{1}{200}$$

$$\omega_s = \frac{1}{\sqrt{C_s L_s}}$$

$$2\pi \times 200 \times 10^3 = \frac{1}{f_s C_s L_s} \quad (1)$$

$$Y_p = \frac{1}{40 \text{ M}}$$

$$\omega_p = \frac{1}{\sqrt{L_s \left( \frac{C_p C_s}{C_s + C_p} \right)}} = 2\pi \times 200 \cdot 25 \text{ kHz} \quad (2)$$

$$\Rightarrow Z_p = \frac{R_s^2 + (Y_{\omega_p} R_p)^2}{R_s} = 40 \times 10^6 \quad (3)$$

from (3)  $C_p = 8.885 \text{ PF}$

$$\Rightarrow \omega_p = \omega_s \sqrt{1 + \frac{C_s}{C_p}}$$

$$C_s = 0.022 \text{ pF}$$

(8)

from ①

$$L_s = 28.488 \text{ H}$$

Q Consider the following statement related to a quartz crystal.

1. Quartz displays ferroelectric behaviour.
  2. Quartz is used in electronic circ.  
ckt.
  3. Quartz crystal is formed by repeating silicate tetrahedral
- which of these statement are true?

D Effective Quality factor of the equivalent electrical ckt of Quartz crystal is of the order of

(a) 20

(b) 200

(c) 200,000

(d) 2000

# Magnetic Properties of Material:

Parameters of magnetic material:

(81)

1. Permeability ( $\mu$ )
2. Magnetic dipole moment ( $\mu_B$ )
3. Magnetization ( $M$ )

• Permeability ( $\mu$ ): It is defined as the ratio of magnetic flux density to magnetic field intensity.

$$\text{i.e. } \mu = \frac{B}{H}$$

where  $B$  = Magnetic flux density  
 $\text{wb/m}^2$  or Tesla

$H$  = Magnetic field Intensity  
 $(\text{A/m})$

Also  $\mu = \mu_0 \mu_r$

where  $\mu_0$  = permeability of free space  
 $= 4\pi \times 10^{-7} \text{ H/m}$

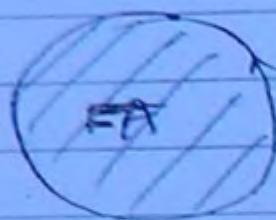
$\mu_r$  = relative permeability (unitless).

• Magnetic Dipole :

A current loop constitute a magnetic dipole.

• Magnetic dipole moment :- It is defined as the product of loop area &

current flowing through the loop.  
it is a vector quantity which  
is directed along normal to the  
plane consisting the current loop.



(82)

magnetic dipole

magnetic dipole moment :

$$\vec{p}_B = i A \hat{n}$$

where  $\hat{n}$  = unit vector along normal  
to the plane consisting the  
current loop.

Unit: (1)  $A \cdot m^2$

\* (2) Bohr magneton : ( $M_B$ )  
Atomic unit of magnetic dipole  
moment is known as bohr magneton

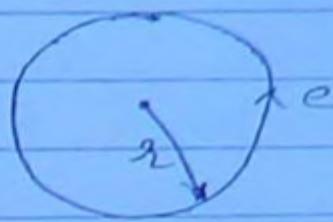
Let us consider an  $e^-$  revolving  
in a circular orbit of radius 'r'  
current flowing through the loop is

$$\vec{i} = \frac{\vec{q}}{T}$$

83

$$\vec{i} = \frac{e}{(2\pi/\omega)}$$

$$\vec{i} = \frac{ew}{2\pi}$$



magnetic dipole moment :

$$\begin{aligned} p_B &= A \vec{i} \\ &= \frac{ew}{2\pi} \times \pi r^2 \end{aligned}$$

$$p_B = \frac{ewr^2}{2} \quad \textcircled{1}$$

Acc to bohr's hypothesis

Angular momentum :

$$mvrs = \frac{nh}{2\pi}$$

where  $n$  = orbit no.

$\hbar$  = plank's const.

$$= 6.626 \times 10^{-34} \text{ J-Sec}$$

$$v = \omega r$$

$$\Rightarrow m(\omega r)r = \frac{nh}{2\pi}$$

$$\Rightarrow \omega = \frac{nh}{2\pi mr^2}$$

from eq. ①

$$p_B = \frac{e\gamma^2}{2} \left( \frac{nh}{2\pi m\gamma^2} \right) \quad 84$$

$$p_B = \frac{neh}{4\pi m} \quad F$$

$$\begin{aligned} 1 \text{ bohr magnetron} &= \frac{eh}{4\pi m} \\ &= \frac{1.6 \times 10^{-19} \times 6.626 \times 10^{-34}}{4\pi \times 9.1 \times 10^{-31}} \end{aligned}$$

$$1 M_B = 9.27 \times 10^{-24} \text{ A-m}^2$$

Larmur's angular freq<sup>n</sup> :- ( $\omega_L$ )

If  $B=0 \Rightarrow \omega = \omega_0$

If  $B \neq 0 \Rightarrow \omega' = \omega_0 + \omega_L$

obj  $\omega_L = \frac{eB}{2m}$

$\omega_L \rightarrow$  it is defined as change in angular freq<sup>n</sup> of orbital e<sup>-</sup> when magnetic field is applied.

## Magnetization ( $M$ ) :-

It is defined as magnetic dipole moment per unit volume.

i.e

$$M = \frac{\mu_B}{\text{volume}}$$

(Q3)

F

$$M = N \mu_B$$

where  $N$  = no. of dipole / unit volume

unit: A/m

the total flux density inside magnetic material is because of 2 factors

- 1) Applied external field intensity.
- 2) Induced magnetization.

$$D = \epsilon_0 E + P$$

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

$\checkmark$  flux density due to external field

$\downarrow$  flux density due to magnetization

$\mu_0$  density of magnetic material

$$\Rightarrow B = \mu_0 (H + M) \quad \dots \textcircled{1}$$

Also

$$B = \mu_0 M H \quad \dots \textcircled{2}$$

from  $\textcircled{1} \& \textcircled{2}$

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

$$M = (\mu_r - 1) H$$

$$\Rightarrow [M = \chi_m H]$$

$$P = \epsilon_0 \times E$$

(86)

where

$\chi_m$  = magnetic susceptibility.

= } +ve material will be attracted by magnetic field  
} -ve material will be repelled away from mag. field.

A magnetic material has a magnetization of  $3300 \text{ A/m}$  & flux density of  $0.0044 \text{ wb/m}^2$ . Calculate - field intensity & relative permeability of material.

$$M = 3300 \text{ A/m}$$

$$B = 0.0044$$

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

$$\mu_r - 1 = \frac{M}{H} = \frac{3300}{\frac{0.0044}{4\pi \times 10^{-7}}} = \frac{3300 \times 7.95}{0.0044} = 7.95 \times 10^7$$

$$\mu_r = 17.26$$

$$H = \frac{B}{\mu_0} - M = \frac{0.0044}{4\pi \times 10^{-7}} - 3300 = 20.3$$

Q find the magnitude of the magnetic flux density in a material for which

(87)

- 1) the magnetization is  $2.8 \text{ A/m}$  & susceptibility is  $0.0025$ .
- 2) the magnetic field intensity is  $1300 \text{ A/m}$  & relative permeability  $\mu_r = 1.006$ .
- 3) there are  $8.2 \times 10^{28} \text{ atoms/m}^3$  each having a dipole moment of  $3 \times 10^{-30} \text{ A-m}^2$  in the same direction  $\Delta x_m = 2 \times 10^{-4}$ .

sol:

$$M = 2.8 \text{ A/m} \quad \left. \right\}$$

$$x_m = 0.0025 \quad \left. \right\}$$

$$H = 1300 \text{ A/m} \quad \left. \right\}$$

$$\mu_r = 1.006 \quad \left. \right\}$$

$$N = 8.2 \times 10^{28} \quad \left. \right\}$$

$$p_B = 3 \times 10^{-30} \text{ A-m}^2 \quad \left. \right\}$$

$$x_m = 2 \times 10^{-4} \quad \left. \right\}$$

$$(1) \quad B = 2.8 = 0.0025 \times H$$

$$H = \frac{2.8 \times 10^4 \times 10^6}{0.0025 \times 10} = 28 \times 40$$

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

$$B = 4\pi \times 10^{-7} (28 \times 40 + 2.8)$$

$$= 1.41 \text{ m wb/m}^2$$

$$(2) \quad B = \mu_0 \mu_r H$$

$$= 1.61 \text{ m wb/m}^2$$

$$(3) M = X_m H$$

$$N P_B = X_m H$$

88

$$H = \frac{N P_B}{X_m}$$

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

$$= \mu_0 \left( \frac{N P_B}{X_m} + M \right)$$

$$B = 1.545 \text{ mwb/m}^2$$

\* Origin of Permanent Magnetic dipole moment:

Whenever a charged particle has angular momentum the particle will contribute to permanent magnetic dipole moment. In general there are 3 contribution to angular momentum of an atom.

- 1) Orbital  $e^-$  angular momentum :- due to orbital motion of  $e^-$ .
- 2)  $e^-$  spin angular momentum :- due to self spin of  $e^-$ .
- 3) Nuclear spin angular momentum :- due to nucleus spin.

Properties of magnetic material: are affected only by  $e^-$  spin angular momentum

(89)

- Electron spin Dipole moment:-
- elements having completely filled orbits have zero resultant  $e^-$  spin moment
- A group of elements having incompletely filled inner orbits are known as transition elements. ex: Fe, Mn, Cr, Sc, Ti etc.

Fe: Atomic no. - 26

electronic configuration :  $1s^2 2s^2 2p^6 3s^2 3p^6$   
 $3d^6 4s^2$

If no. of  $e^-$  in incompletely filled inner  $3d$  orbit is "z"

$$\text{If } z < 5 \Rightarrow \mu_B = z M_B$$

$$\text{If } z > 5 \Rightarrow \mu_B = (10-z) M_B$$

for Fe:  $\mu_B = (10-6) M_B = 4 M_B$

Ferrous ions:-

$Fe^{2+}$  :  $1s^2 2s^2 2p^6 3s^2 3p^6 3d^6$

$$\begin{aligned} \mu_B &= (10-6) M_B \\ &= 4 M_B \end{aligned}$$

$Fe^{3+}$  :  $1s^2 2s^2 2p^6 3s^2 3p^6 3d^5$

$$\mu_B = 5 M_B$$

8 The outer most electronic configuration of a cobalt atom is  $3d^7 4s^2$  its magnetic moment is.

(9)

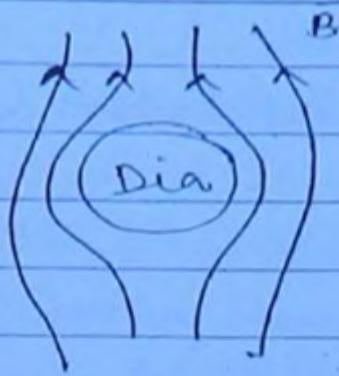
- (a) 9  $M_B$
- (b) 7  $M_B$
- (c) 5  $M_B$
- (d) 3  $M_B$

### \* Classification of Magnetic Material:

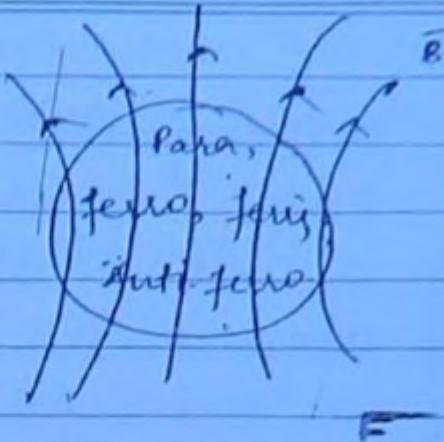
- |                       |                   |       |
|-----------------------|-------------------|-------|
| 1. Diamagnetic        | $\chi_m$<br>(-ve) |       |
| 2. Paramagnetic       | {                 |       |
| 3. Ferromagnetic      |                   | —     |
| 4. Anti-ferromagnetic |                   | (+ve) |
| 5. Freni-magnetic     |                   |       |

#### 1. Diamagnetic material:-

- these materials do not have permanent dipole.
- these material are having small  $\chi_m$  value of magnetic susceptibility.
- these material repelled away from applied magnetic field.
- for these materials magnetic susceptibility is independent of temp.



(91)



for diamagnetic material :

$$B = 0$$

$$\Rightarrow \mu_0 (H+M) = 0$$

$$\Rightarrow H+M = 0$$

$$\Rightarrow M = -H$$

$$\Theta = -\chi_m H$$

$$[\chi_m = -r]$$

$$\mu_r - 1 = -r$$

$$\Rightarrow [\mu_r = 0] \rightarrow \text{perfect diamagnetism}$$

$\mu_r = 0$  or perfect diamagnetism is one of the necessary condition for a material to be a super conductor.

ex. of diamag.

Cu, Au(gold), Ge, Si, Diamond,  
NaCl, Al<sub>2</sub>O<sub>3</sub> etc.

2. Paramagnetic materials: (92)  
these materials when placed in  
a magnetic field  
acquire a weak magnetization  
in the same dir<sup>n</sup> of field.  
therefore small & the magnetic  
susceptibility.

In paramagnetic material, dipole  
moment of atom & ions have  
no mutual int<sup>r</sup>action.  
However in the presence of field,  
the magnetic moment have a  
tendency to turn towards the  
dir<sup>n</sup> of magnetic field if no  
opposing force acts, complete  
alignment of dipoles will be  
produced and specimen as a  
whole would acquire a very large  
magnetization in the direction of  
field. but thermal agitation of  
atoms opposes this tendency and  
tends to keep the dipole moment  
at random. this results only a  
partial alignment of dipoles along  
the field direction. therefore a  
weak magnetization and small  
the susceptibility. the effect of ↑

in temp<sup>r</sup> is to ↑ the thermal-agitation  
of dipoles and ∴ susceptibility ↑.

(93)

Some paramagnetic material follow curie law.

Curie Law :-

$$M = \frac{N\beta_B^2}{kT} \cdot H$$

$$\boxed{M = \frac{C}{T} \cdot H}$$

where  $C$  = Curie constant

$$= \frac{N\beta_B^2}{K}$$

Ex:  $\text{NiSO}_4$ ,  $\text{Mn SO}_4$ ,  $\text{FeSO}_4$ ,  $\text{FeCl}_2$ ,  
 $\text{Fe}_2\text{O}_3$  etc.

some paramagnetic material do not obey curie law and these materials obey curie-weiss law.

Curie-weiss law:

$$M = \frac{N\beta_B^2}{kT} H_i \quad \text{--- (1)}$$

$$\& H_i = H + \gamma M$$

from (1)

$$M = \frac{N\beta_B^2}{kT} (H + \gamma M)$$

$$\Rightarrow M \left( 1 - \frac{N p_B^2 \cdot \gamma}{kT} \right) = \frac{N p_B^2 \cdot H}{kT}$$

(94)

$$\Rightarrow M = \frac{N p_B^2 / kT \cdot H}{1 - \frac{N p_B^2 \cdot \gamma}{kT}}$$

$$M = \frac{\frac{N p_B^2}{k} H}{T - \frac{N p_B^2 \cdot \gamma}{k}}$$

$$M = \frac{C \cdot H}{T - \Theta} \rightarrow \text{Curie Weiss Law.}$$

(2)

$$\text{where } C = \text{Curie const.} = \frac{N p_B^2}{k}$$

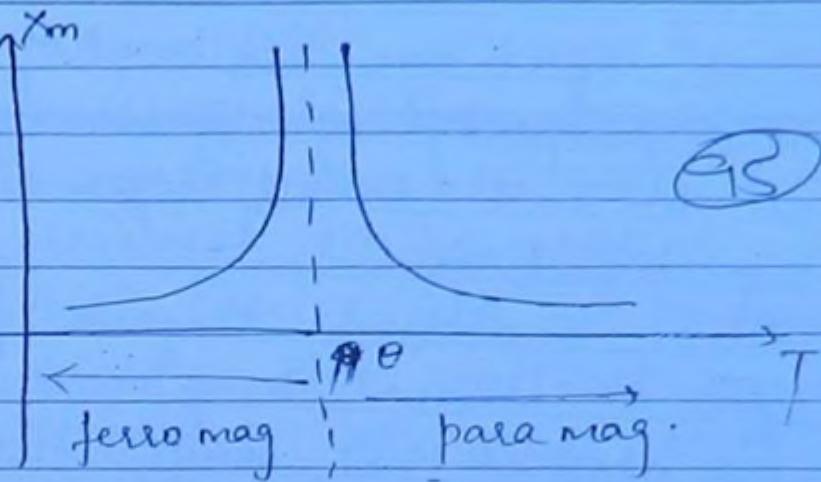
$$\Theta = \text{Curie temp.} = \frac{N p_B^2 \cdot \gamma}{k}$$

$$\gamma = \text{internal field const.} = \frac{\Theta}{C}$$

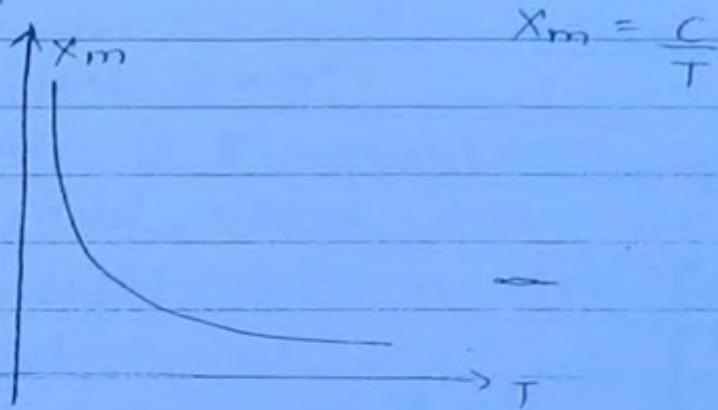
$$\text{Also, } M = X_m H \quad \text{--- (3)}$$

from (2) & (3)

$$X_m = \frac{C}{T - \Theta}$$



Curie Law:

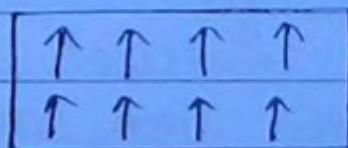


$$\chi_m = \frac{C}{T}$$

Magnetic susceptibility  $\uparrow$  for ferromag. materials & it  $\downarrow$  in case of para mag. materials.

3. Ferromagnetic materials :-

- these materials are characterized by  $11^{\text{th}}$  alignment of dipole.



- these material get magnetize in the dir<sup>n</sup> of applied field & remain magnetized

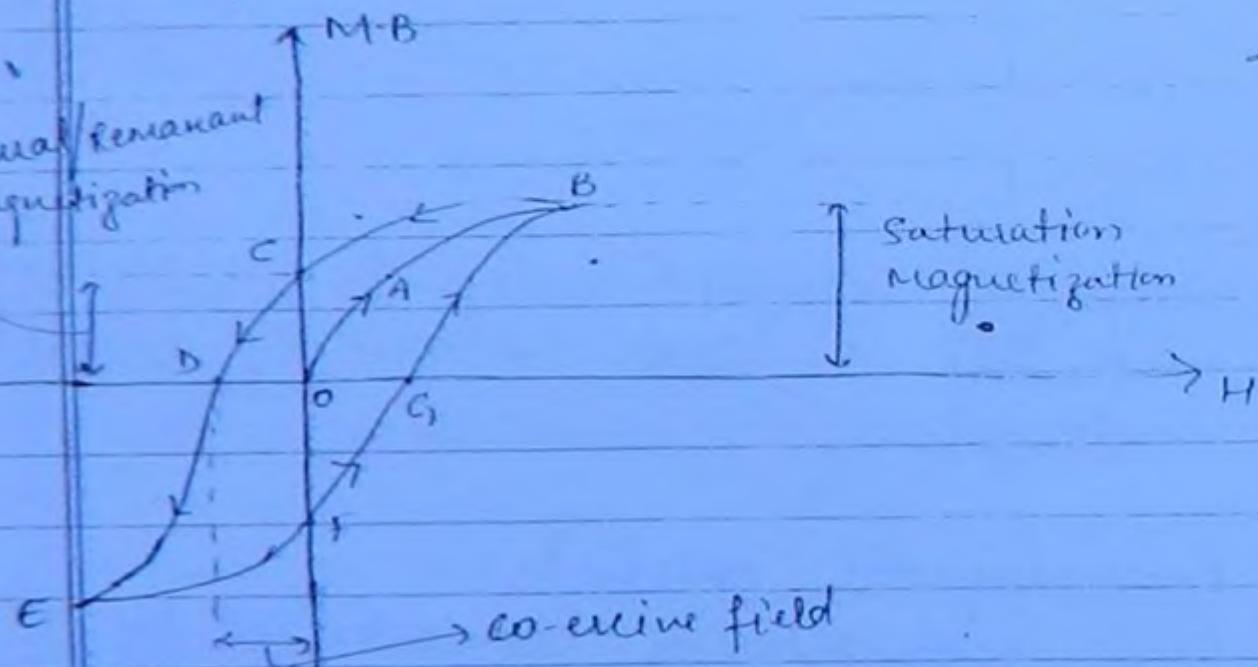
even after the removal of field.

This property of ferromagnetic material is called spontaneous magnetization.

(96)

These materials remain ferromagnetic upto a critical temp<sup>o</sup> called Curie temp<sup>o</sup> and above this temp<sup>o</sup> these materials start behaving like paramagnetic material.

Hysteresis curve :



When a magnetic field is applied to a ferromagnetic material, the material follows the path OAB in the hysteresis curve. When the field is reduced to zero magnetization does not reduce to zero but retains a

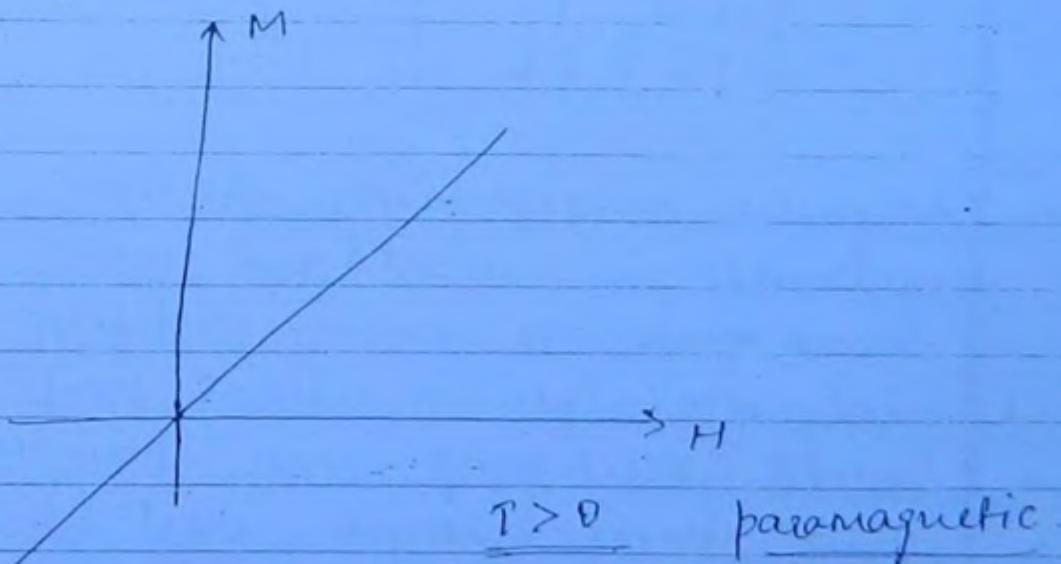
non zero magnetization known as residual/ remanent magnetization. To reduce this residual magnetization to zero a magnetic field is required to be applied in opposite dir<sup>n</sup>. This field is known as coercive field. The material never comes back to its original state once it is expose to magnetic field.

(97)

Above curie temp<sup>r</sup> :-

As temp<sup>r</sup> is ↑, the area of hysteresis loop b. and above curie temp<sup>r</sup> this loop merges into a straight line

Magnetization w



Ex: Fe, Co, Ni, Gd (Gadolinium), Dy (Dysprosium)  
etc.

## Material

Cuie Temp<sup>r</sup> (°K)

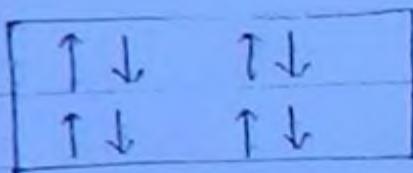
(98)

Co	1404
Fe	1043
Ni	631
Gd	889

4.

Antiferro magnetic Materials:

These materials are characterized by antiparallel alignment of dipole. So the net magnetization is zero when no external field is applied.



- Magnetic susceptibility for these materials is small and the
- these materials remain antiferro magnetic upto a critical temp<sup>r</sup> called "Neel temp" and above this temp<sup>r</sup> these materials start behaving like paramagnetic materials. The relationship b/w magnetization and field intensity is governed by a law very similar to curie-wieß law.

$$X_m = \frac{C}{T + \Theta_N}$$

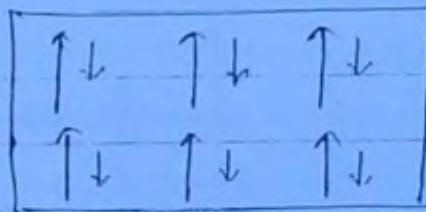
(99)

where  $\Theta_N$  = Neel temp.

Ex:-  $MnO$ ,  $MnD_2$ ,  $CoO$ ,  $FeO$  etc.

### 5. Ferrimagnetic Material:-

these materials are also having dipoles with anti parallel arrangement but they are not equal.



these materials posses net magnetization in one dir<sup>n</sup> (it means non-zero spontaneous magnetization)

these materials remain ferrimagnetic upto a critical temp<sup>r</sup> called curie temp<sup>r</sup> and above this temp<sup>r</sup> these materials start behaving like paramagnetic materials.

the advantage of these materials are higher dc resistivity than ferromagnetic materials. because of this property

ferrides are having lesser eddy <sup>(Tz)</sup> current losses as compared to ferromagnetic materials. due to this reason ferrides are used for the construction of core of high freq<sup>+</sup> transformers & inductors.

Properties of ferrites:

1. High resistivity.
2. Low eddy current losses.
3. High permeability.
4. High dielectric constant
5. High curie temp.
6. Extremely low dielectric losses

Classification of ferrites based on application:-

- Hard ferrites
- soft ferrites
- Rectangular ferrites
- microwave ferrites

- Hard ferrites: these are used in permanent magnet.
- 1. these materials are having high coercive field.
- ex Ba & Sr ferrites

Soft ferrites :- these ferrites are having low coercive field these are used for the construction of core of high freq<sup>n</sup> transformers and inductors.

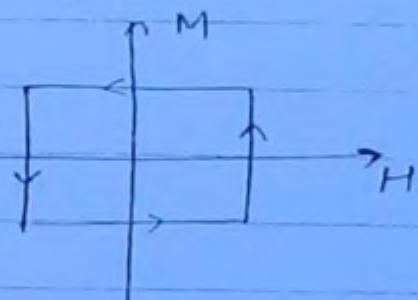
Ex:- Mn-Zn ferrites

(10)

Ni-Zn ferrites → used in audio & TV transforms..

Rectangular ferrites:

These ferrites are having rectangular shape of hysteresis curve



These are used in magnetic memories.

Ex:- Mn-Mg ferrites

Mn-Cu ferrites

Ni-Li ferrites

microwave ferrites :- These are used at microwave freq<sup>n</sup>. At these freq<sup>n</sup> the EM wave interact with the spin-magnetic moment of e<sup>-</sup> due to which plane of polarization of EM wave

gets rotated by some angle.

This phenomenon is called Faraday rotation.

- Ex: Co-ferrites, Mn-ferrites, Ni-ferrites, Garnets

Application:

Isolators

Circulators

Gyrators.

(YIG)

Garnets

Yttrium-iron

Garnets

(TO2)

- Another classification of ferrites:

- Ferrites from Magnetite



where M = Divalent element

(Mg, Zn, Co, Cd, etc.)

- Ferrites from Garnets:



Rare earth ferrites

- Q Ferrites can be considered as mixed oxides of metals A & B. Their formula can be written as

(a)  $ABO_3$

(b)  $A_2BO_3$

(c)  $AB_2O_3$

(d)  $AB_2O_4$

## Magnetic Anisotropy :-

In some magnetic materials, the magnetic properties depend on the direction in which they are measured. This property of magnetic material is called magnetic anisotropy. There are three methods to induce magnetic anisotropy.

- 1) Cold working
- 2) Magnetic annealing
- 3) Magnetic Quenching

(103)

- 1) Cold working :- (Heating & forcefully cooling).

Cold working such as cold rolling induces uniaxial magnetic anisotropy in the direction of rolling.

- 2) Magnetic Annealing:- (Slow heating & slow cooling). :-

In this process heat treatment is done in the presence of magnetic field in order to induce magnetic anisotropy.

- 3) Magnetic Quenching:- (Heating & fast cooling).

In this process the material is cooled down to curie temp<sup>r</sup> in the presence of magnetic field. The magnetic

quenching induces anisotropy either in the direction of field or TOY in a direction perpendicular to the field.

Magnetostriction :-

when the magnetic materials are magnetized changes in dimension are generally observed this property of material is called magnetostriction.

there are 3 types of magnetostriction

- 1) longitudinal
- 2) Transverse
- 3) Volume

Longitudinal : when changes in dimension are parallel to field, magnetostriction is called longitudinal.

Transverse : when changes in dimension (produced strain) are perpendicular to the field, magnetostriction is called transverse.

Volume :- when changes in dimension are proportional to field as well as L to the field, magnetostriction is called volume.

(ToS)

Note:- Magnetostriction is responsible for humming noise in the core of transformer

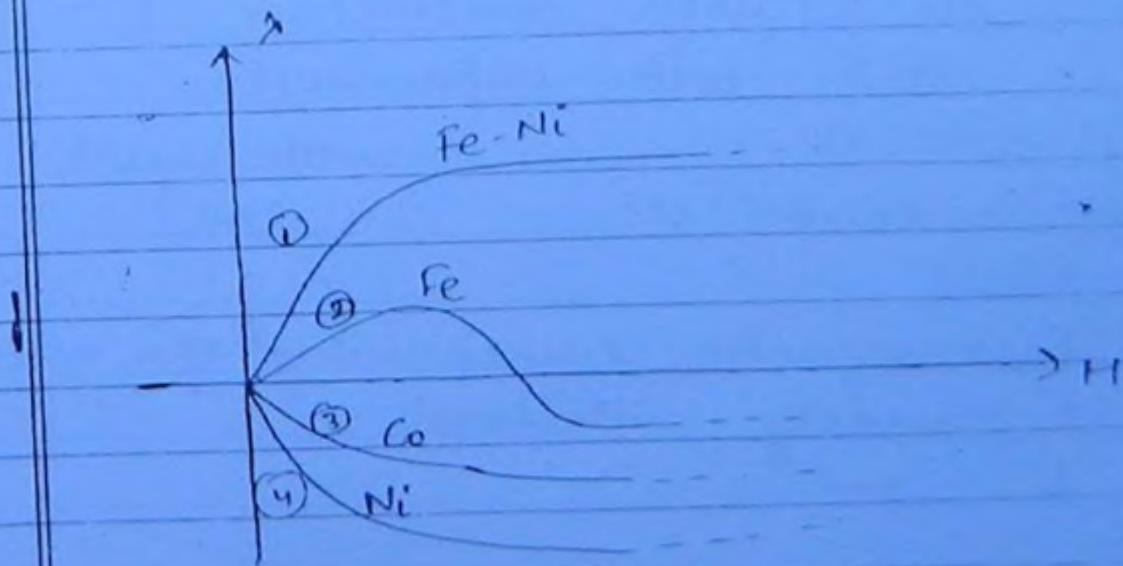
$$\text{strain}(\lambda) = \frac{\Delta L}{L}$$

+ve magnetostriction

- Material expands with ↑ in field strength
- Material contracts when field strength ↓
- etc. Fe Ni alloys

-ve magnetostriction

- Material expands when field strength ↓
- Material contracts when field strength ↑
- etc Co, Ni etc



Application of Magneto striction :-

1. Generation of supersonic sound
2. Generation of high freq oscillations
3. Under water sound detection

(16)

\* Villari effect:-

- It is converse of magneto striction
- the longitudinal deformations leads to change in magnetic permeability "in the dir" of applied mechanical stress

Case 1 - Material with +ve strain ( $+\lambda$ )

$\mu_B \uparrow$  with expansion

$\mu_B \downarrow$  with contraction

ex: Fe Ni alloys

Case 2 material with -ve strain

$\mu_B \uparrow$  with contraction

$\mu_B \downarrow$  with expansion

ex: Co, Ni etc

B

Paramagnetic susceptibility of a material

(a)  $\uparrow$  linearly with temp

(c) T linearly with  $1/T$

(d)  $\downarrow$  " "

Ans

(c)

$$(X_m) = \frac{C}{T}$$

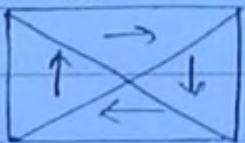
$$Y = CX$$

(107)

\*

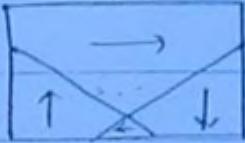
Ferro magnetic domain :- (conv.)

$$H = 0$$



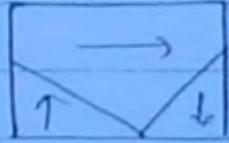
(a)

$$H \neq 0$$



(b)

$$H \neq 0$$



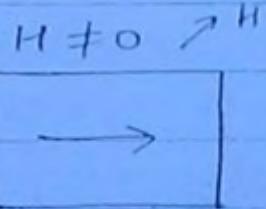
(c)

(a) - fresh magnetic material

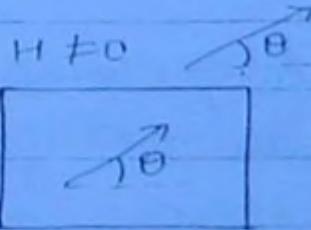
- Net magnetization is zero

- Multidomain state

(b) Growth of single domain



(d)



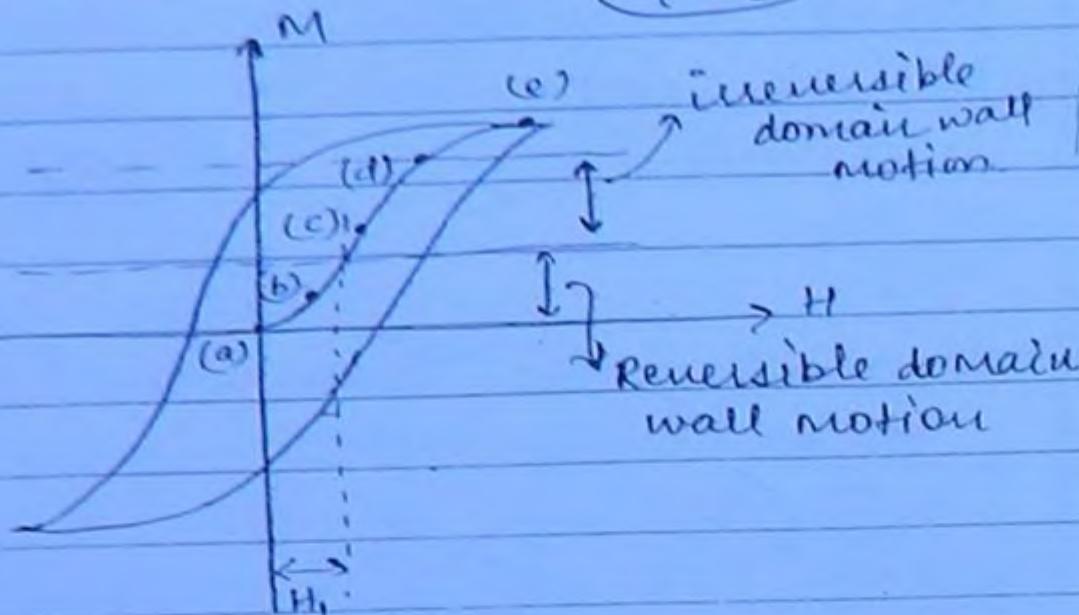
(e)

single domain  
state

Rotation of domain  
toward applied  
field

Hysteresis curve:

108



If  $H < H_i \Rightarrow$  displaced domains once again will take their position on removal of field

- slope of graph =  $X_m$
- initial permeability is low

A ferromagnetic material is divided in no. of small regions. each region is spontaneously magnetized but the dir<sup>n</sup> of magnetization varies from one region to another region these regions are called ferromagnetic domain. initially material have zero spontaneous magnetization as shown in fig. (a) [multi domain state]. when a

field is imposed on the material, domains are lined up with field grow at the expense of unaligned domains. as shown in fig. (b) and (c). [conversion from multidomain to single domain state]. This process continues until only the most favourable domain remain in the material as shown in fig (d). When the domain growth is completed a further ↑ in magnetic field causes domains to rotate and aligned  $11^{\circ}$  to the field as shown in the figure (e). At this instant material reaches saturation magnetization & no further ↑ will take place on ↑ the strength of external field.

Q Which of the following are the properties of ferromagnetic materials

- 1) Permanent magnetism
- 2) Atomic moments in individual domains are aligned neither  $11^{\circ}$  to nor  $\perp$  to one another below curie temp<sup>x</sup>
- 3) Each domain is magnetically saturated
- 4) Above curie temp<sup>x</sup> domains disrupt (disorder)

which of these statement are correct?

1, 3 & 4

8

During the process of magnetization of ferromagnetic materials the magnetic domains:

(110)

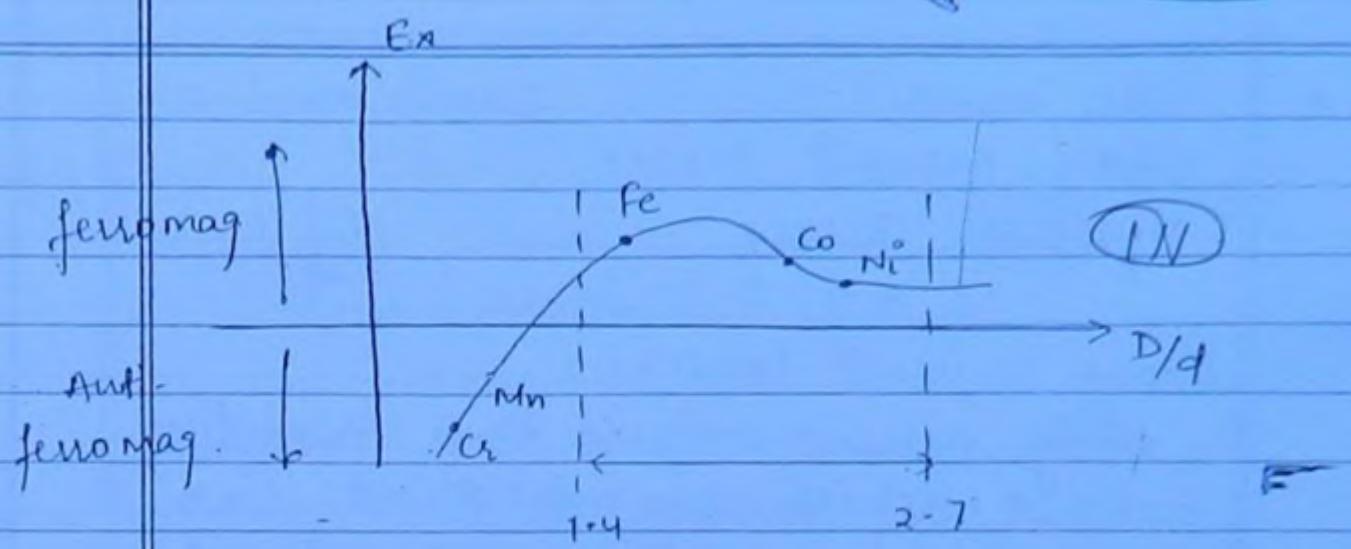
- 1) Only expands
- 2) rotate 1<sup>st</sup> & then expands
- 3) Neither rotates nor expands
- 4) expand 1<sup>st</sup> & then rotate.

(obj) \* Exchange Interaction Energy:

- the 11<sup>th</sup> alignment of magnetic dipoles of iron, cobalt and Nickel atoms is due to presence of energy known as exchange interaction energy.
- It is f<sup>n</sup> of the ratio of atomic diameter (D) to 3-D orbital diameter.

$$E_x = f \left[ \frac{\text{atomic diameter (D)}}{\text{3-d-orbital diameter (d)}} \right]$$

- for 11<sup>th</sup> alignment to occur, the ratio must be in the range b/w 1.4 to 2.7.



\* Comparison b/w magnetic material :-

Material	$\chi_m$	" $\chi_m$ Vs "T"	Alignment of dipoles	Examples
Diamagnetic	-ve & small $(\approx -10^{-5})$	$\chi_m$ is independent of 'T'	no dipoles	$Cu, Au, Si, Ge,$ Diamond, $Al_2O_3$ , NaCl etc
Paramagnetic	+ve & small $(\approx 10^{-5})$	$\chi_m = \frac{C}{T}$ Curie law or $\chi_m = \frac{C}{T + \theta}$ Curie Weiss law	$\uparrow \downarrow \uparrow \downarrow$	$FeSO_4, NiSO_4,$ $MnSO_4, FeCl_3,$ $Fe_2O_3, Cr_2O_3$ etc
Ferromagnetic	+ve & very large	$\chi_m \rightarrow \infty$	$\uparrow \uparrow \uparrow \uparrow \uparrow \uparrow$	$Fe, Co, Ni,$ Gad, Dy, etc
Anti-ferro	+ve & small	$\chi_m \rightarrow$ saturation	$\uparrow \downarrow \uparrow \downarrow \uparrow \downarrow$	$NiO, CoO,$ $MnO_2, MnO,$ FeO etc
Ferrimagnetic	+ve & large	$\chi_m \rightarrow \infty$	$\uparrow \downarrow \uparrow \downarrow \uparrow \downarrow$	Ferrites

\* Core losses:-

- Eddy current losses
- hysteresis losses.

(112)

Eddy current losses:-

eddy current refers to a circulating current which are introduced in a sheet of conducting material when it is subjected to alternating magnetic field.

eddy current loss is given by

$$\text{P}_{\text{eddy}} (\text{Watt/m}^2) = \frac{\pi^2 f^2 B^2 t^2}{\rho \beta}$$

where  $f$  = freq<sup>n</sup> of ac field

$B$  = magnetic flux density

$\rho$  = resistivity

$t$  = thickness of material

$\beta$  = material constant

→ As  $f \uparrow \rightarrow$  eddy current losses  $\uparrow$

so to reduce losses at higher freq<sup>n</sup> iron cores are laminated or si-steel is used. (5% si). (higher resistivity).

these materials are used at higher freq<sup>n</sup> in the core of transformers

& inductors.

Hysteresis Losses :-

(113)

$$P_{\text{Hys}} \text{ (watt/m}^3) = \eta B^n f$$

where  $\eta$  = constant

$B$  = applied field

$f$  = freq. of ac field

$n$  = an exponent.

Hysteresis loss  $\propto$  area of hysteresis loop

- Soft ferrites or soft magnetic materials have less co-ercive field and hence less area of hysteresis loop. (low hysteresis losses) - so they are used in high freq. electromagnetic devices.
- Soft & Hard magnetic materials :-

Refractivity :- the value of residual flux density is called refractivity.

Co-ercentivity :- the max. value which of co-ercentive field can attain is called coercivity.

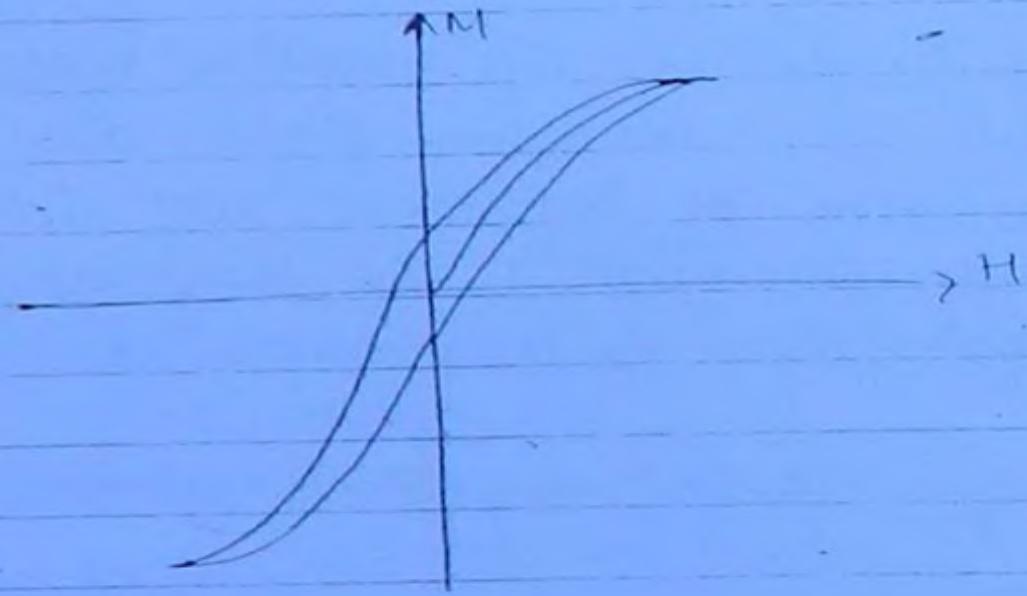
soft magnetic materials :-

- these materials are easy to magnetize & demagnetize.
- these materials favours rapid switching of magnetization to the applied ac field.

114

Properties :-

1. Low ~~degree~~ retentivity.
2. Low co-ercentry.
3. High saturation magnetization.



4. Low hysteresis losses (because of narrow hysteresis loop)
5. High permeability.

- these materials are desirable for transformer & inductor cores to minimize energy dissipation

- These are desirable for electromagnets.
- Ex:- ① Fe-Si alloy / soft iron / Si steel (5% Si)
- These are used upto power frequencies (upto 100 Hz)
- It is used in power transformer
- When 5% Si is added it ↑ permeability, resistivity and reduces area of hysteresis loop
- Less eddy current losses and hysteresis losses.

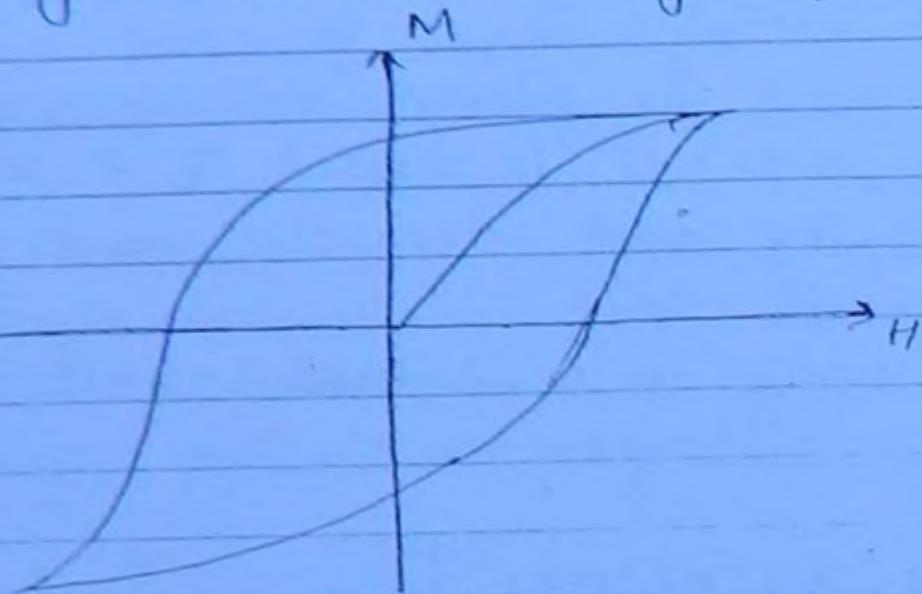
- ② Fe-Ni alloys
- Permalloy (45% Ni)
  - Super alloy (79%)
  - Mu metal alloy (75%)

- These alloys are having high resistivity and less area of hysteresis loop
- Hard Magnetic Materials :-
- These materials are also known as permanent magnet materials.
- They are so these materials retain their magnetization and difficult to demagnetize.

Properties :-

1. High retentivity
2. High coercivity
3. High saturation magnetization.

(116)



4. Higher hysteresis losses because of wide hysteresis loop
  5. High permeability
  6. High curie temp.
- because of high retentivity & high coercivity these are used for the construction of permanent magnet.
- ex -
    - ① Carbon steel
    - ② Tungsten steel
    - ③ AlNiCo ( $\text{Al} + \text{Ni} + \text{Co}$ )
    - ④ Unite ( $\text{Cu} + \text{Ni} + \text{Fe}$ )
    - ⑤ Ba-ferrite
    - ⑥ Remalloy.

Carbon steel :- it is used as magnets for latch relays and compass needle

Tungsten steel: it is used as magnets for dc motors.

(117)

Alnico : these magnetic properties are very stable with time & temp.

Q for permanent magnetic material

- ✓ a) the residual induction at the co-cursive field should be large.
- b) the residual induction at the coercive field should be small.
- c) the area of hysteresis loop should be small.
- d) the initial relative permeability should be large.

Q Consider the following statement -

In a transformer the core material should have low -

- 1) Co-currivity
- 2) retentivity
- 3) Permeability

Ans 1 & 2

8

How can eddy current loss in the core of a transformer be minimized?

(118)

- 1) by ↑ the resistivity of core.
- 2) by using laminated sheets with insulator coatings.
- 3) By using highly insulating non-magnetic material for the core.
- 4) By using the paramagnetic material at the core.

sol:

1 & 2 are correct.

8

The hysteresis loop for the material of the core of a transformer should be

- (a) short & narrow
- (b) short & wide
- (c) tall & wide
- (d) tall & narrow

Q

Consider the following statement:  
 At finite temp., magnetic dipoles in a material are randomly oriented giving low magnetization with when magnetic field is applied the magnetization :

- 1) ↑ with H
- 2) ↓ " H
- 3) ↓ with Temp° for const. H.

sol:

2 & 3 are correct.

Q

Match list 1 & list 2.

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List 1

List 2

A Permanent Magnet

1. Ferrites

B High freq. (MHz) appl<sup>n</sup>

2. Hard-mag. materials

C Electromagnets

3: Garnets

D Very high freq (GHz) appl<sup>n</sup>

4. Soft mag. material

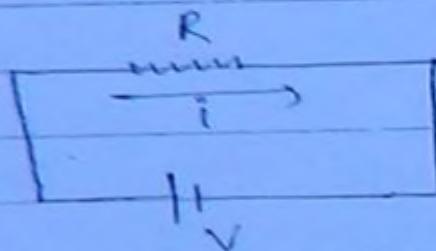
# Conductor / Insulator / Semiconductor :-

(120)

## \* Conductor :-

Ohm's law (Point form):

$$\boxed{J = \sigma E}$$



$$V = iR \quad \text{resistivity}$$

$$\Rightarrow V = i \left( \rho \frac{L}{A} \right)$$

$$\Rightarrow \frac{i}{A} = \frac{V}{\rho L}$$

$$j = \left( \frac{V}{L} \right) \left( \frac{1}{\rho} \right)$$

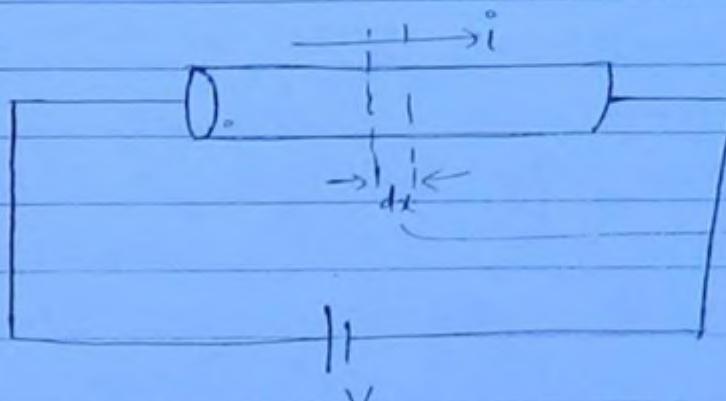
$$\boxed{J = \sigma E}$$

Under the influence of electric field the motion of  $e^-$  has 2 component directed motion due to applied external field.

2. Random motion which depends on temp<sup>r</sup>. 121

Derivation for conductivity:

Let us consider a conductor having current  $i$  & applied voltage  $V$



, time taken  
by one to  
cover distance  
'dx' is 'dt'

force experienced by  $e^-$  under the influence of external field

$$F = m \frac{d^2x}{dt^2} = -eE$$

$$\Rightarrow \frac{d^2x}{dt^2} = -\frac{eE}{m}$$

$$\Rightarrow \frac{dx}{dt} = -\frac{eE}{m} \cdot t + v_{\text{random}}$$

drift velocity of  $e^-$  is defined for average collision time which is the average time b/w 2 successive collisions of  $e^-$ . over avg. collision time random velocity is zero.

$$\Rightarrow \frac{d\mathbf{v}}{dt} = \frac{eE}{m} \tau - \text{avg. collision time}$$

↑ drift velocity

(122)

Also,

$$v_d = -UE$$

from eq.(1),

$$v_d = -\left(\frac{e\tau}{m}\right) E$$

$$= -UE$$

$$\boxed{\mu = \frac{e\tau}{m}}$$

current density:

$$J = -ne v_d$$

$$= -ne \left(-\frac{e\tau}{m} E\right)$$

$$= \frac{ne^2 \tau}{m} E$$

$$J = \sigma E$$

$$\boxed{\sigma = \frac{ne^2 \tau}{m}}$$

[ Avg. collision time: ]

$$\tau \propto \frac{1}{f_T}$$

for metals / conductors :-

$$\sigma \propto nT$$

(723)

$$\sigma \propto \frac{n}{\sqrt{T}}$$

As  $T \uparrow \rightarrow$  there is no appreciable increase in carrier concentration but significant decrease in avg. collision time therefore, with  $T$  in temp<sup>o</sup> conductivity decreases in case of conductors / metals

For semiconductors :-

$$\sigma \propto nT$$

$$\sigma \propto \frac{n}{\sqrt{T}} \quad \text{--- (7)}$$

Also,

$$n^2 = n_i^2 = A_0 T^3 e^{-E_{c,o}/kT}$$

$$n = A_0^{1/2} T^{3/2} e^{-E_{c,o}/2kT}$$

from eq. 7,

$$\sigma \propto \frac{T^{3/2} e^{-E_{c,o}/2kT}}{\sqrt{T}}$$

$$\Rightarrow \sigma \propto \frac{T^{\frac{1}{2}}}{e^{E_{c,o}/2kT}}$$

In sc. conductivity  $\propto$  with  $T$  in temp<sup>2</sup> because the  $\propto$  in carrier conc<sup>n</sup> dominates over the decrease in avg. collision time.

(124)

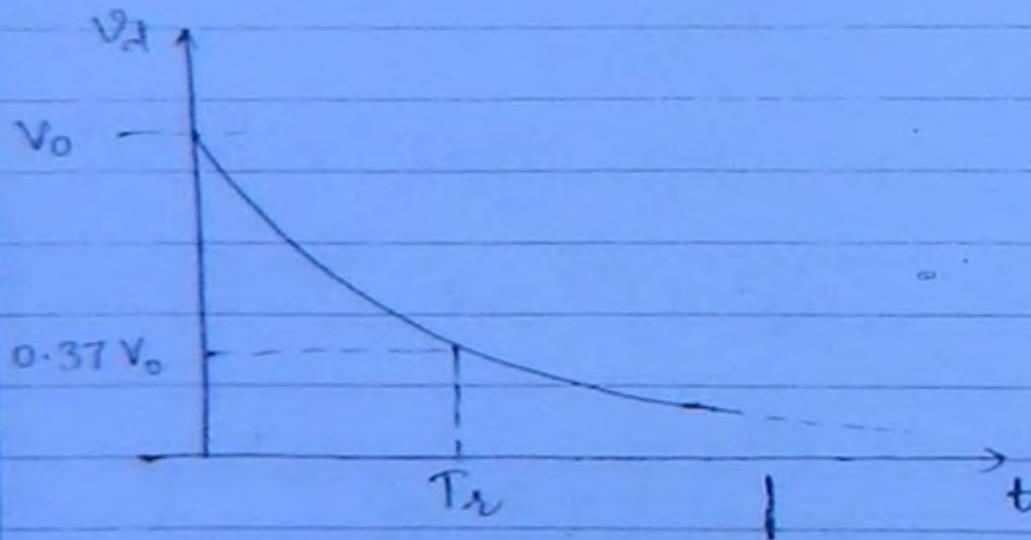
- \* Mean free path ( $\lambda$ ) :-

It is defined as the avg. distance travelled by  $e^-$  b/w 2 successive collisions.

$$\boxed{\lambda = V_d \cdot T}$$

- \* Relaxation time ( $T_r$ ) :-

It is defined as the time required at which the drift velocity of  $e^-$  reduces to 37% of its value after the removal of electric field.



for isotropic material relaxation time is equal to avg. collision time.

\* Factors affecting resistivity of metals.  
- Temperature  
- Alloying.

(123)

Temperature :-

$$\rho_2 = \rho_1 [1 + \alpha (T_2 - T_1)]$$

where  $\alpha$  = temp. coefficient of resistivity <sup>(<sub>°</sub>C/m)  
 $\rho_2$  = resistivity at temp "T<sub>2</sub>"</sup>

$$\rho_1 = " " " " T_1 "$$

Alloying :-

If an alloy is formed by mixing 2 metals then total resistivity will be greater than individual resistivity of metals.

Matthiessen's Rule :-

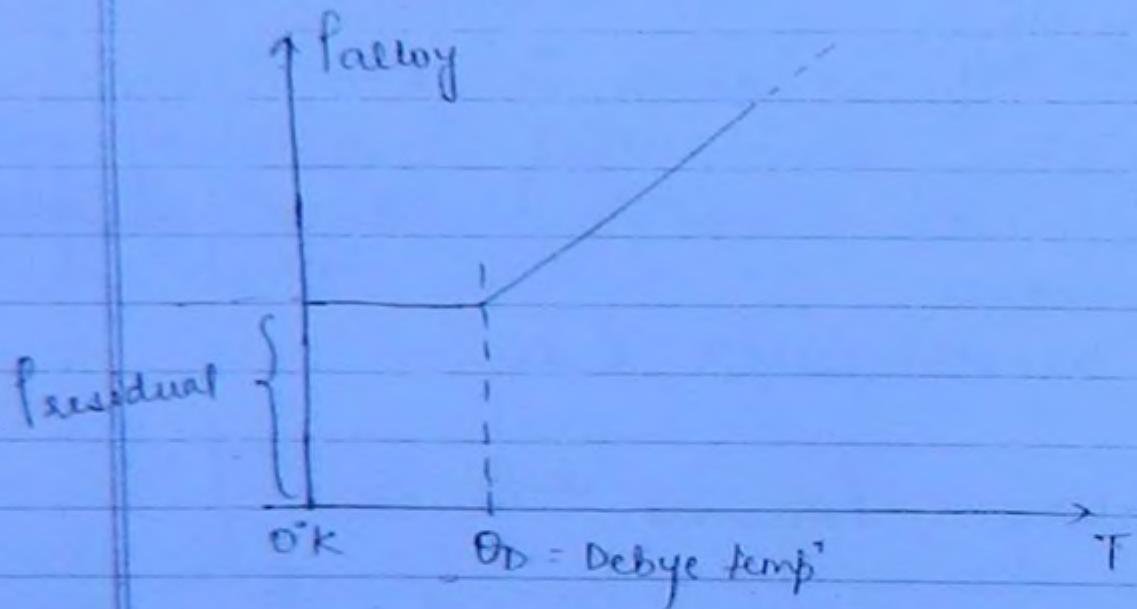
$$[\rho_{\text{alloy}} = \rho_{\text{metal}} + \rho_{\text{residual}}]$$

Resistivity of alloy has 2 component  
1. Metal resistivity :- this component  
2. arises due to lattice vibration  
in the material which ↑ with temp  
this can be ↓ to zero by reducing the

temp° to 0°K.

(126)

2. Residual component :- this component arises due to impurities and defects present in the material. this component is independent of temp°.
- At 0°K alloy does not have zero value of resistivity because of residual component.
  - Above temp° called "Debye" temp° resistivity of alloy T linearly with temp°.

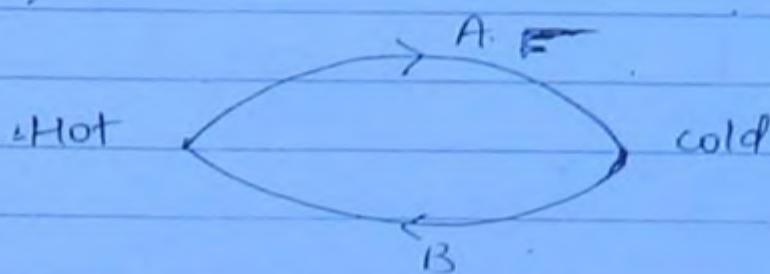


Q)  $\rightarrow$  Thermo electric effects :-

- Seebeck effect
- Peltier effect.

Seebeck effect :-

when 2 dissimilar metals are joined at their ends and jn ends are maintained at different temp<sup>r</sup> then an emf exist across the jn



(127)

Peltier effect :-

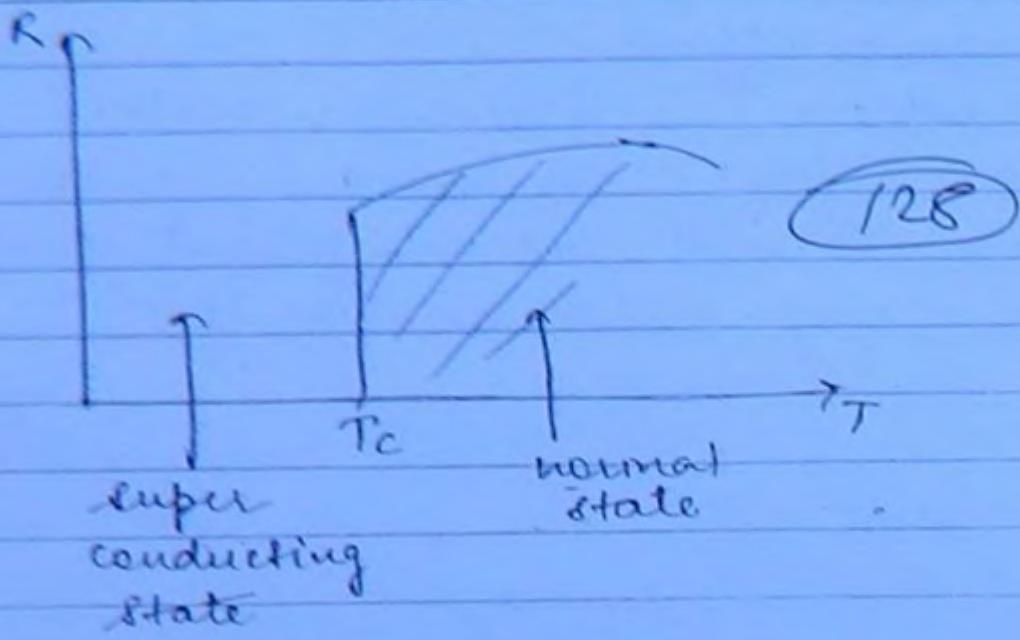
It is converse of seebeck effect

An electric current which flows through a rod consisting of 2 different metal causes a  $\Delta$  in temp<sup>r</sup> at one end and  $\tau$  in temp<sup>r</sup> at the other end.

\* Superconductors :-

Superconductivity :- A state of material in which it has zero resistivity is called superconductivity.

Transition temp<sup>r</sup> :- ( $T_c$ ) the critical temp<sup>r</sup> at which there is change of state from superconducting to normal & vice-versa is called transition temp<sup>r</sup>.



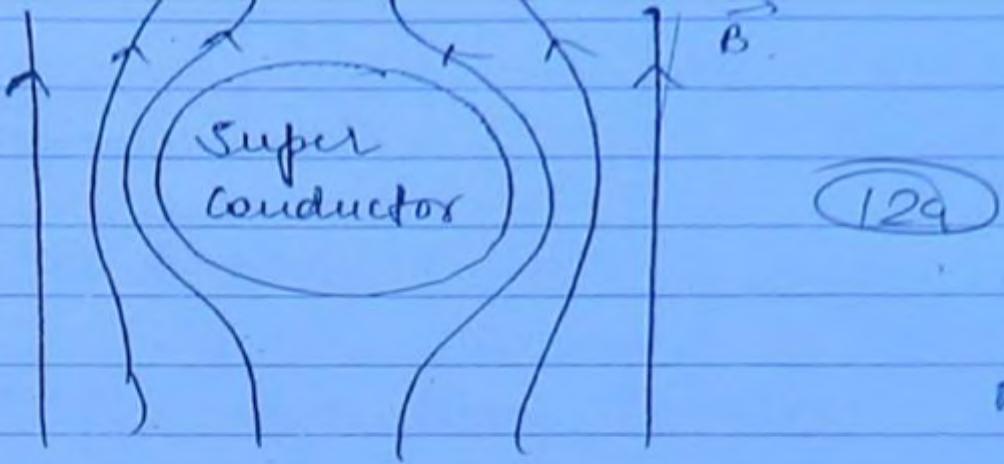
transition from superconducting to normal state & vice-versa  
- is reversible. -

Super conductors:-

The materials whose resistivity become very small or zero below a critical temp<sup>n</sup> are called superconductors.

Meissner's effect :-

The repulsion of magnetic flux line from the interior of a piece of super conducting material as the material undergoes the transition to the super conducting state is known as meissner's effect.



Total flux density,

$$B = 0$$

$$\Rightarrow \mu_0(H+M) = 0$$

$$\Rightarrow H+M = 0$$

$$\Rightarrow M = -H \quad \text{--- (1)}$$

$$\text{Also, } M = \chi_m H \quad \text{--- (2)}$$

from (1) & (2)

$$\chi_m = -1$$

$$\Rightarrow \mu - r = -r$$

$$\Rightarrow \boxed{\mu = 0} \rightarrow \text{perfect diamagnetism}$$

Condition for superconductivity :-

Resistivity should be zero.

$\mu = 0$  or perfect diamagnetism

Critical field ( $H_c$ ) :-

It is the min. field required at a given temp<sup>r</sup> to destroy superconductivity.

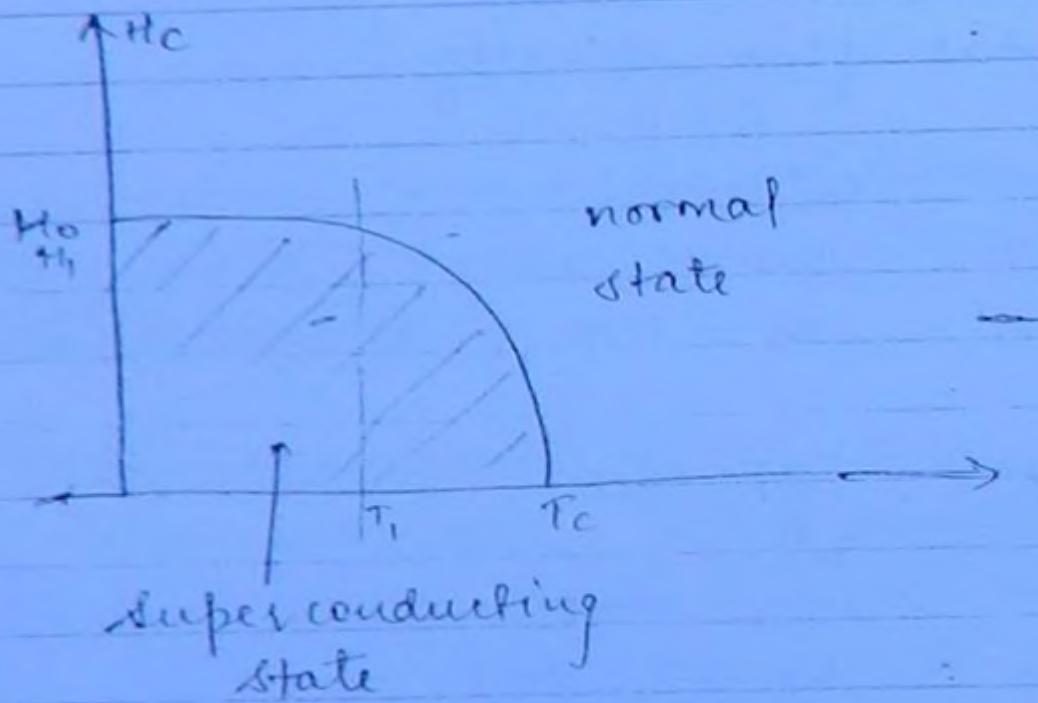
& it is given by

$$H_c = H_0 \left[ 1 - \left( \frac{T}{T_c} \right)^2 \right] \quad (130)$$

where  $H_0$  = critical field at 0°K

$T_c$  = transition temp.

$H_c$  = critical field required at  $T$



Transition temp<sup>r</sup> can be reduced by applying external magnetic field

Q the critical field for Niobium is  $1 \times 10^5$  A/m at 8K and  $2 \times 10^5$  A/m at 0°K calculate the critical temp<sup>r</sup> ( $T_c$ ) of material.

Ans  $H_0 = 2 \times 10^5$  A/m

$$H_c = 1 \times 10^5$$

$$T = 8\text{ K}$$

$$10^5 = 2 \times 10^8 \left[ 1 - \left( \frac{B}{T_c} \right)^2 \right]$$

$$\frac{1}{2} = \left[ 1 - \left( \frac{B}{T_c} \right)^2 \right] \quad (131)$$

$$\left( \frac{B}{T_c} \right) = \frac{3}{2}$$

$$T_c = 11.31 K$$

### \* Silsbee Rules :-

If a superconducting materials carries a current such that the magnetic field which it produces is equal to critical field, the superconductivity disappear this rule is silsbee rule.

The current density at which the superconductivity disappear is called critical current density.

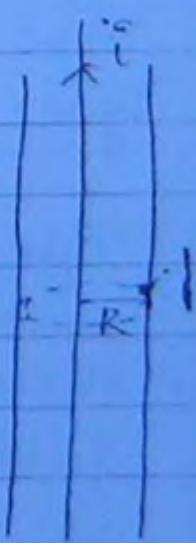
Let us consider a long wire of superconducting material having a central current  $i$ .

acc. to amper's law.

$$\oint H \cdot dL = i$$

$$\Rightarrow H \cdot 2\pi R = i$$

$$i_c = 2\pi R H_c$$



Critical current density :-

$$\therefore J_c = \frac{I_c}{A}$$

(132)

$$= \frac{2\pi R H_c}{\pi R^2}$$

$$J_c = \frac{2H_c}{R}$$

This rule prevents the use of superconductor as coils for the production of strong magnetic field.

The field required to destroy the superconductivity need not be an external field, it may be internal field also.

Types of superconductors :-

Type I

Type II

Type I :- these are ideal or soft superconductors.

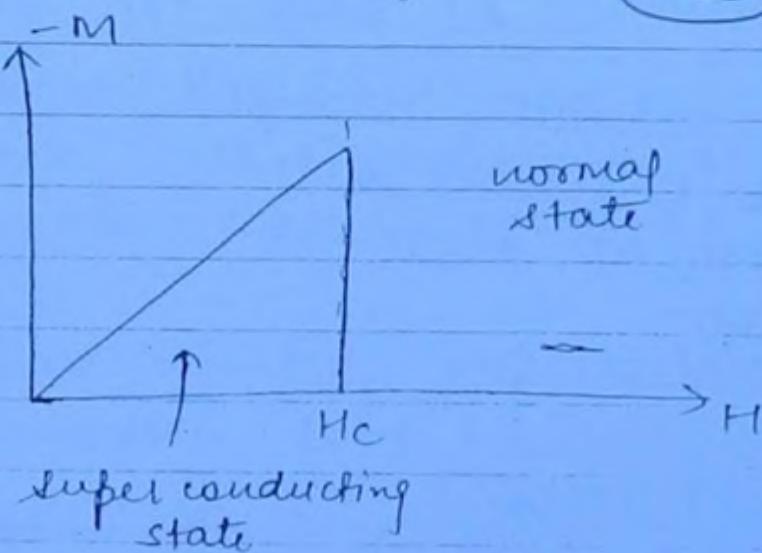
• their critical temp<sup>r</sup> and critical field are low.

- the change of state from normal to superconducting & vice-versa is abrupt.
- they exhibit complete Meissner's effect and Silsbee rule.
- ex. Pb, Pd, Zn, Hg, Al, Ta etc.

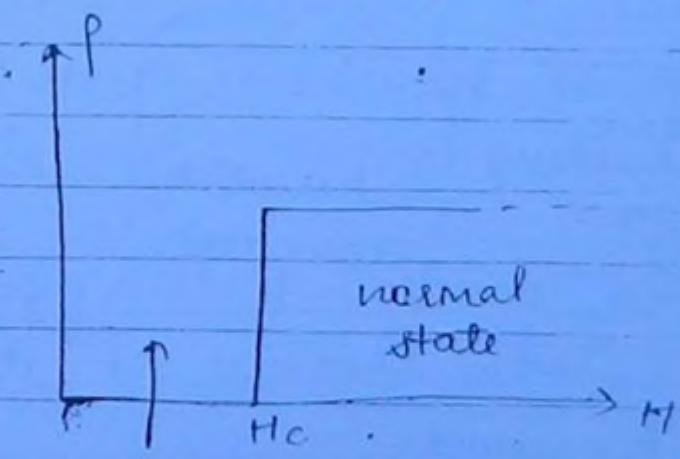
$$\rightarrow M = -H$$

$$\Rightarrow -M = H$$

(133)



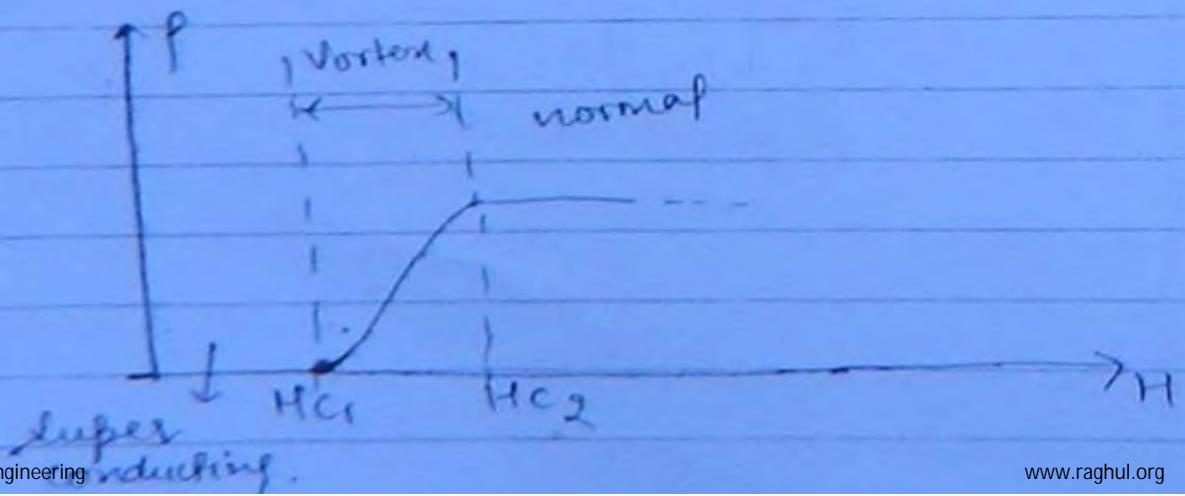
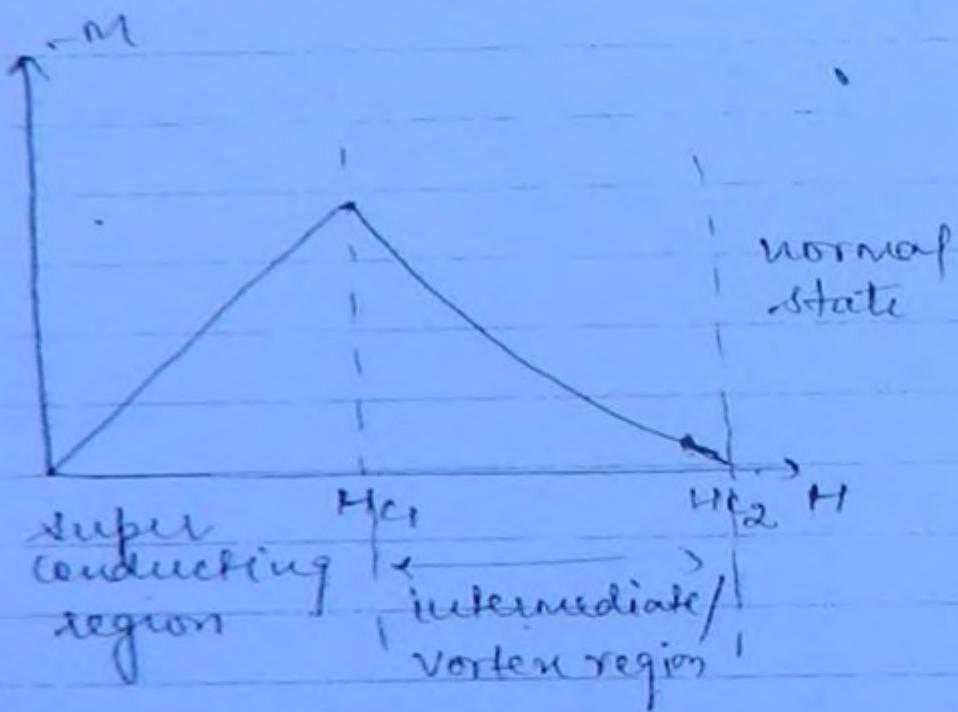
"P" vs "H":



• superconducting state

## Type-II :-

- these are also known as non-ideal or hard superconductor  
here critical temp. & critical fields are high  
the change of state from normal to superconducting & vice-versa is gradual.  
they exhibit incomplete meissner effect & silsbee rule  
ex:  $\text{Nb}_3\text{Al}$ ,  $\text{NbTi}$  etc



Q1. In vortex region Meissner's effect is incomplete.

(133)

Application of super conductor:

1. These are used for magnets for "nuclear fusion".
2. They are used in motors & generators.
3. They are used in magnetic resonance imaging (MRI).
4. These are used in switching elements like "cavotrons".

factors affecting superconductivity & transition temp:-

1. Frequency :- with  $T$  in freq<sup>n</sup> superconductivity  $\downarrow$ . It is observed upto radio freq<sup>n</sup> (upto 10 MHz). Above 10 MHz resistivity  $\uparrow$  and at infrared freq<sup>n</sup> the resistivity is same as normal state.
2. Entropy :-  $\uparrow T$  from superconducting state to normal state.
3. Thermal conductivity :-  $\uparrow T$  from superconducting state to normal state.

4. Isotope mass :-

$$T_c \propto \frac{1}{\sqrt{M_{\text{atom}}}}$$

at Hg : 199.6 → 203.4 AMU  
 $T_c$  :  $4.185^\circ\text{K}$  ↓  
 $4.16^\circ\text{K}$

$$\text{Hg} \Rightarrow T_c \approx 4.1^\circ\text{K}$$

(136)

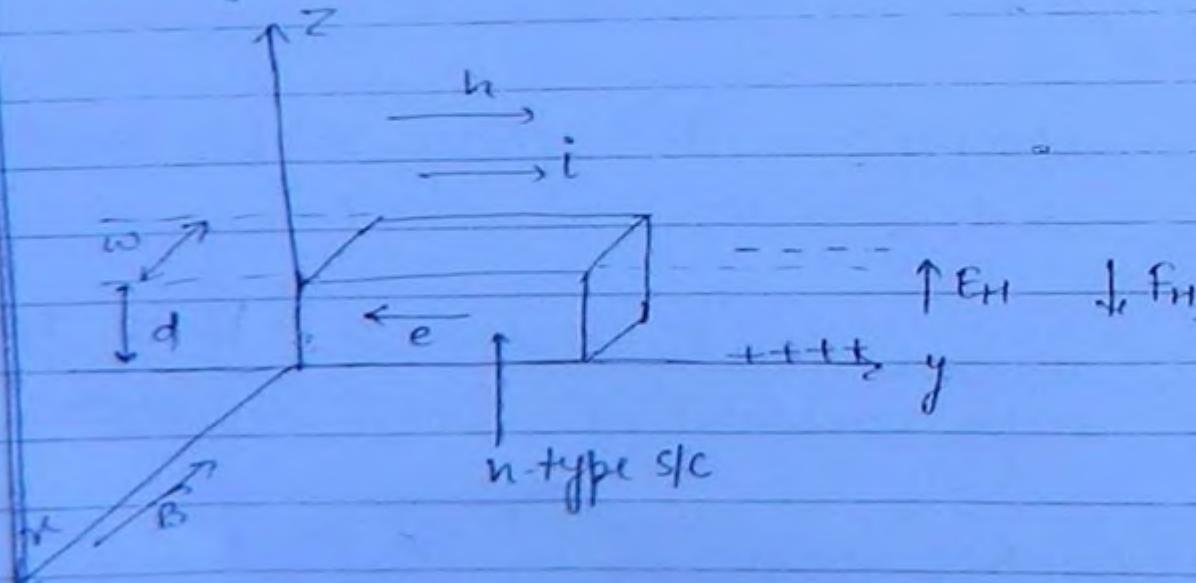
### 5. Mechanical stress / Pressure :-

Transition temp<sup>r</sup> of superconducting materials changes with applied mechanical stress.

for ex: there are some metals like Cs. that become superconducting only if a large p<sup>r</sup> is applied.

### \* Hall Effect :-

Princi when a current carrying specimen is placed in a transversed magnetic field then an electric field is induced  $\perp$  to both current & magnetic field.



Lorentz force:

$$\vec{F}_L = q(\vec{v} \times \vec{B})$$

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Let us consider n-type S.C. Suppose an electric current is flowing in the y dir<sup>n</sup> and magnetic field is applied -ve rad<sup>n</sup>. A force called Lorentz force is exerted on e<sup>-</sup> as well as on holes in the z dir<sup>n</sup>. The minority hole will recombine with majority e<sup>-</sup>. The movement of e<sup>-</sup> in upward dir<sup>n</sup> thus + disturb local net neutrality of S.C.

The app<sup>n</sup> of Lorentz force will result in the formation of a -ve layer on the top surface of S.C. (due to excess e<sup>-</sup>) and formation of +ve layer takes place on the bottom surface (due to +ve ions). An electric field will induce in upward dir<sup>n</sup>, which is called Hall field.

At equilibrium

$$F_H = F_L$$

$$\Rightarrow eE_H = eV_B B$$

$$\Rightarrow \frac{V_H}{d} = V \cdot B$$

$$\rightarrow J = \rho V d$$

↳ charge conc<sup>n</sup>

$$V = V_d = \frac{i}{\rho}$$

(738)

$$\Rightarrow V_H = V B \cdot d$$

$$= \frac{I}{\rho} B \cdot d$$

$$V_H = \text{Hall-voltage}$$

$$= \frac{B \cdot d}{\rho} \cdot \frac{i}{A}$$

$$V_H = \frac{B \cdot d}{\rho} \cdot \frac{i}{d \cdot w}$$

$$V_H = \frac{Bi}{\rho w}$$

$$V_H = R_H \frac{Bi}{w}$$

where  $R_H$  = Hall coefficient

$R_H = \begin{cases} \frac{1}{\rho}, & \text{when particle is moving} \\ & \text{with drift velocity.} \end{cases}$

$\left. \frac{8\pi}{3\rho} \right\}, \text{when speed is random.}$

$$R_H = \begin{cases} -ve, & n\text{-type} \\ +ve, & p\text{-type} \end{cases} \quad (B9)$$

for comparable  $e^-$  & hole concentration  
 $R_H$  is calculated by.

$$R_H = \frac{1}{e} \cdot \frac{p u_p^2 - n u_n^2}{(p u_p + n u_n)^2}$$

for intrinsic s.c. :-

$$n = p = n_i$$

$$R_H = \frac{1}{e} \cdot \frac{n_i (u_p^2 - u_n^2)}{n_i^2 (u_p + u_n)^2}$$

$$R_H = \frac{1}{n_i e} \frac{(u_p - u_n)}{(u_p + u_n)}$$

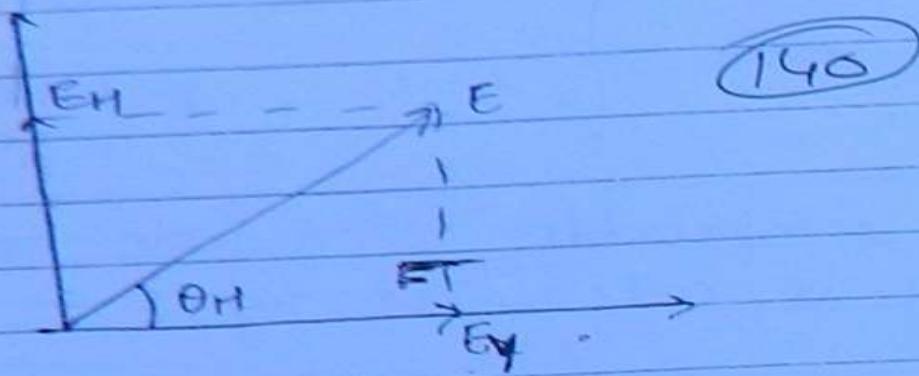
$$u \propto \frac{1}{M_{eff}}$$

since  $u_p < u_n$   
 $R_H = -ve$

for ex:  $R_H = -ve$  & large, intrinsic s.c.

	$R_H$
Ge	$-10^6$
Si	$-10^9$

Hall angle :- ( $\theta_H$ )



$\theta_H$  = Hall angle

$$\tan \theta_H = \frac{E_H}{E_Y}$$

$$\tan \theta_H = \frac{(v_H/d)}{\left(\frac{J_y/\sigma}{\rho}\right)} \quad \therefore J_y = \sigma E_y$$

$$= \frac{v_H \cdot \sigma}{d} \cdot \frac{1}{J_y}$$

$$= \left( \frac{B i}{\rho w} \right) \cdot \frac{1}{d} \cdot \frac{\sigma \cdot A}{i}$$

$$\tan \theta_H = \frac{B \sigma}{\rho}$$

$\rho \rightarrow$  charge density.

$$[\sigma = \rho \cdot \mu]$$

$$\tan \theta_H = B \cdot \mu$$

$$\Omega_H = \tan^{-1}(\mu B)$$

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Applications of Hall effect :-

- (1) To determine type of s.c.
- (2) To determine carrier conc'.
- (3) To determine mobility of carriers
- (4) It is used in Hall effect multiplier.
- (5) It is used in magnetic field meter.

\* GaAs :-

- It has a large bandgap
- It has large  $e^-$  mobility which helps in high speed switching.
- It is direct bandgap material. (used in LEDs)
- Crystal structure is Zinc blend
- In GaAs crystal, Ga atom occupies corner and face atoms whereas As atom occupies whole 4 inferior atom.
- GaAs is 10 times costlier than Si
- GaAs based devices are 2.5 times faster than Si based devices.

Applications:-

1. It is used in satellite amp<sup>r</sup>.
2. High freq<sup>r</sup> devices
3. LEDs

#### 4. LASERS.

TYC

- In GaAs ~~not~~ group VI impurities serve as donors.  
ex: S, Se, Te etc.
- In GaAs group II impurities serve as acceptors.  
ex: Be, Zn, Cd etc.
- "Amphoteric"  
when GaAs is doped with grp IV impurities, these impurities can serve as donors or acceptors.  
These impurities are called "Amphoteric".
- In GaAs, Si is wafer preferred as a donor (replaces Ga)
- In GaAs Ge is preferred as an acceptor.

## I. Low resistivity conducting materials:

Science

- Used in house-wiring, power transmission & distribution, winding of transformers and machines like motors and generators. (143)
- Ex: Cu, Al, Ag, Brass, Bronze etc.
- Silver(Ag) has lower resistivity than Cu but its very high cost restricts its commercial use.
- Al is cheaper than Cu. So it is often used as a Cu substitute in electrical power system.

Platinum - used for contact fabrication in low melting point contacts.

Nickel - Used for making electrodes.

Lead - poor conductor

- Because of anti-corrosion properties used for covering of underground & underwater cables for power & communication lines.

Brass: Cu-Zn alloy ( $Zn = 45\%$ )

- High tensile strength but lower conductivity than Cu.
- Good solderability & good anti-corrosion properties.

- used in plug points, lamp holders, sliding contact for starters & rheostats etc.
- Si, Ti, Al, Mn brasses have higher electrical resistance.

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Bronzes - Alloy of Cu & Tin, Al, Ni, Si.

- Superior mechanical properties & Anti-corrosion properties than brasses.
- Types:

Phosphor Bronze:

Used in current carrying springs, dials, brush holders etc.

Silicon Bronze: Cables & telephone tools.

Solders: It is an alloy which is used to join two or more pieces of metals. The melting point of solder is lower than the materials to be joined.

Types:

(i) Soft solder:

- used for temperature less than  $400^{\circ}\text{C}$ .
- alloy of tin & lead (Pb).

(ii) Hard solder:

- |  |  |
|--|--|
| <ul style="list-style-type: none"> <li>- used at temperature higher than <math>400^{\circ}\text{C}</math>.</li> <li>- Alloy of Cu &amp; Zn.</li> </ul> | <ul style="list-style-type: none"> <li>- Braze solder is used at high temp.</li> <li>- Silver solder.</li> </ul> |
|--|--|

## \* High resistivity conducting materials

According to application high resistivity alloys are divided into 3 categories:

(i) Material used for precision electrical measuring instruments. 143

- For this, material must have stability of resistance with time and temperature.

Ex: Manganin.

ii) Materials used for resistance elements:

- low cost & permissible working temperature

- Ex: Constantan

iii) Materials used for furnaces & heating devices:

- Must have high melting point

- Ex: Nichrome.

### \* Comparison % (V.V.I)

Alloys	composition	$\rho$ at 20°C ( $\Omega \cdot m$ )	operating temp.	Application
Nichrome	Mn+Cr+Mn+Fe	$100 \times 10^{-8} \Omega \cdot m$	upto 1100°C	heating elements in soldering iron, furnaces etc.
Constantan	Ceet+Ni	$52 \times 10^{-8} \Omega \cdot m$	upto 500°C	wire-wound resistors, Rheostat, strain gauges etc
Manganin	Ceet+Mn+Ni	$48 \times 10^{-8} \Omega \cdot m$	$\approx 60^\circ C$	Precision instruments. Bridge potentiometers etc.
Tungsten (not high resistive)	metal	$5.61 \times 10^{-8} \Omega \cdot m$	3300°C	heating filaments such as bulbs, (R.T.s etc.)

## \* Insulators<sup>80</sup>

### ① Ceramics . Properties:

- (146):
- Inorganic materials
  - generally crystalline (exception - Amorphous Glass).
  - these are hard, strong, dense & brittle.
  - Higher temperature stability
  - Excellent dielectric properties.
  - Ceramics are stronger in compression than in tension.

Ex: Garnets, Borosil, Cement, Ferrite, TiO<sub>2</sub>,  
Quartz, MgO, CaS, ZnO, SiC, Si<sub>3</sub>N<sub>4</sub>,  
ZnS etc

### Types:

- i) Porcelain: Used in low & high voltage application.  
( $\epsilon_r < 12$ ) - used as insulator in transmission  
distribution, plugs and sockets etc.
- ii) Silicate: - used in high frequency application.  
( $\epsilon_r < 12$ )
- iii) Alumina: ( $\text{Al}_2\text{O}_3$ ) - ( $\epsilon_r < 12$ )
  - High temperature applications.
  - Used in circuit breakers, resistance cores etc.
- iv) Titanate: (Titanite) - ( $\epsilon_r > 12$ )
  - capacitor applications due to high dielectric constant.

## Another classification of ceramics

### (i) $\epsilon_r > 12$ :

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- Used for capacitor application due to high dielectric constant.
- They are based primarily on mineral "Rutile ( $TiO_2$ )" & on titanates  $\text{Fe}^+$

### (ii) $\epsilon_r < 12$ :

- Used as insulators because of low dielectric constant.
- Ex- Steatite, Alumina, Porcelains etc.

## Transformer oil:

- Transformer cores & chokes are dipped immersed in mineral oil known as transformer oil which acts as insulator. It also acts as a cooling medium.
- Parameters determining the properties of transformer oil
  - specific gravity
  - flash point
  - pour point
  - viscosity
- Contamination decreases breakdown voltage.
- To absorb moisture (contaminant), absorbents are added to the oil. The absorbents used are Silica ( $SiO_2$ ) & alumina ( $Al_2O_3$ ).

1. Carbon composition:

- Non-inductive resistor used in RF circuits.
- Power rating is upto 2 watts.
- These resistors have large tolerances.

2. Film resistors:

- Types? Metal films, Carbon film, Metal oxide film
- low power rating upto 0.25 watt.  
(unable to handle large power).
- Resistances are of higher values & have low tolerances & low noise.
- Metal film ? Better temperature stability.  
Metal-oxide film ? High surge current capability.  
Thick film resistors ? Cermet (ceramic metal)

3. Wire wound resistors:

- high power rating ( $\approx$  300watt)
- Inductive type, low resistance & high precision
- Due to inductive properties they are not used in audio & RF circuits.
- used in measuring circuits & wheatstone bridge

4. Ceramic Resistors:

- Non inductive, high power resistor
- Also called cermets.
- Thick film resistors with good temperature stability, low noise but low surge current handling.

## Capacitor types:

### Insulating materials

- 1. Mica Capacitor:
  - temp.  $\rightarrow$  High vdg. resonance chf.  $\downarrow$
  - High stability
  - Good temp & freq. characteristics  $\curvearrowright 149$
  - Demerit: Moisture can affect adversely  
proper coated is required.
- 2. Paper Capacitor:
  - To increase the stability & reduce the power losses, the paper is now replaced by a thin layer of polystyrene.
- 3. Electrolytic Capacitors:
  - Inexpensive
  - Creates capacitance per unit vol.
  - lowest cost per microfarad.
  - The electrolyte that is used in electrolytic cap. should be maintained at a potential lower than the Al-foil, otherwise the layer of Al-oxide which constitutes the dielectric will be destroyed.
  - low freq bypass for this reason the 2+ve signs up are marked on these capacitors.
  - Used at low/audio freq. power supplies (filter cap.)
- 4. Variable Capacitors:
  - Plates are made of Al, Brass, Cd.
  - Air acts as dielectric.
- 5. Ceramic Capacitors:
  - Disc style capacitors.
  - Small, reliable & cost effective
  - High dielectric const., good thermal stability, moisture proof.
  - Dominetly used nowadays.
  - Often used for bypass and coupling appln.

