HAND WRITTEN NOTES:--

OF

ELECTRICAL ENGINEERING

SUBJECT:--

ELECTRICAL MATERIALS
Syllabus:

1. Chemical bonding & structure of solid
2. Dielectric material & its properties
3. Magnetic material & its properties
4. Insulator — Ceramic

Semi-Conductor — \[
\begin{cases}
ESM \text{ (elemental semi material)} \\
CSM \text{ (Compounded semi material)}
\end{cases}
\]

Conductor — Super conductor

\( \text{SiC} \rightarrow \text{IV Compound semiconductor} \)

Valency: 4
**Chemical bonding & structure of Solid**

Chemical bonding → The binding forces b/w atoms of molecules are known as chemical bond. There are two types of chemical bond.

(a) Primary
(b) Secondary

(a) Primary → These bond are interatomic bond

(ii) These bond are having higher bond energy

Ex: Ionic, Covalent & metallic bond.

(b) Secondary → These bonds are intermolecular bond.

These bonds are having lesser bond energy as compared to primary bond.

Ex: Vander Waals bond
Hydrogen bond.

(i) Ionic bond → The ionic bond is a bond resulting from the electrostatic interaction of oppositely charged ions by transfer of one electron from one to another.
Ionic Solid are formed particularly elements on the left & right hand side of the periodic table. Ex (Group 1 + Group 7)

Group 1 elements are 'Alkalis' element (Li, Na, K, Rb, Cs, Fr).

Group 7 element are 'Halogens' (Br, Cl, I, F).

The Alkali halide form b/w the Alkalis metal + the halogen are strongly ionic.

General chart of Solids having Ionic bond →

1. Higher strength
2. Higher melting point
3. Hard
4. Electrically insulator
5. Brittle. (Can be break).
6. Malleable (Can be shaped). (Tensile).

Covalent Bond → These bond are form by sharing of e⁻ b/w neighbouring atom. Ex- Si, Ge, CO₂

General chart of material having Co-valent bond →

1. Very hard
2. Very brittle
3. Very high melting point.
4. Conductor $\rightarrow$ Tin (Sn)
   Semi-Cond $\rightarrow$ Si, Ge
   Insulator $\rightarrow$ Diamond.

Metallic bond $\rightarrow$ The outer most $\epsilon$ of metal atom are weakly bound & become when such atom interact to become a solid whose electron form a gas of electron known as electron gas or electron cloud. The valence electron in a metal cannot be associated with a particular atom. They belong to all atom.

General characteristics $\rightarrow$

1. Higher thermal & electric property
2. Metals are opaque
3. They are having surface luster
4. Metallic bonds are non-directional. (It means bond strength is equal in all direction)
   The highest degree of metallic bonding occurs in alkali metal.
Vander-Waals bonding: An electron revolving around a neutral atom may be considered to represent a rotating dipole. Such a dipole will induce a dipole in a neighboring atom such that a dipole attraction between the atoms results. These weaker bonds are known as van der Waals bonds. Examples include solid Ar, solid He, and solid hydrogen.

Inert or rare gases are examples of van der Waals bonding. Hydrogen bond is a strong type of van der Waals bonding.
Atomic arrangements in Solids

- Crystallinity
- Single Crystal
- Poly - Crystalline material.
- Amorphous.
- Epitaxial.

Crystallinity

Property of Solid in which atoms or molecule are stabbed in a regularly or ordinary manner.

Single Crystal

If the atom are stabbed in regular manner then it is called single crystal.

Ex - Quartz

These materials are unisotropic. (Property of naterial varies with direction)

Poly Crystalline Material

It consist of grains with in which atomic molellia with essentially regular but showing irregularities and as one goes from one grain to another.

These material are generally isotropic because of random distribution of grains.
Single Crystal:

Poly-crystal Material:

Amorphous:

Atoms of two first nearest neighbouring atoms are arranged periodically but the atom which are away from the nearest atom are found to be arranged randomly. When the atom are not given opportunity to arrange them selves in an orderly manner by inhibiting mobility during solidification Amorphous material may be formed.

Ex. Super cooled states of SiO$_2$, correspond to glass (Amorphous material).

Where as upon Annealing (slower heating & cooling) may crystallise into Quartz.
In other cases the molecules may be extremely long and irregular in shape so that orderly arrangement may not obtain as in the case of polymer.

(5) **Epitaxial** → (Used for growth of Si)

It refers growth of a layer of Si on a substrate.

**Structure of Solids**

(1) **Unit Cell** → Minimum area cell in 2 dimension

Or minimum volume cell in 3-d.

by repetition of... which crystalline solid may be generated.

**Important properties of unit cell** →

1. Cell dimension
2. Angle b/w axis
3. No. of atoms per unit cell.
4. Co-ordination no. (It is no of atoms which are in physical contact with a particular atom.

5. **Atomic Packing Factor (APF)** →

\[
\text{APF} = \frac{\text{Sum of total atomic Volume of per unit cell}}{\text{Volume of unit cell}}
\]
Lattice

Orderly or periodical arrangement of unit cell is called lattice.

unit-cell.

Cubic - Crystal Structure

- Diamond Cubic (DC)
- Simple Cubic (SC)
- Face Centred Cubic (FCC)
- Body Centred Cubic (BCC)

1. Simple Cubic

$\rightarrow 3d$

$\rightarrow 2d$
no. of atoms per unit cell = $\Theta \times \frac{1}{a} = 1$

In simple cubic there are $\Theta$-atoms or $\Theta$-corners of the cube.

\[ \text{Co-ordination no.} = 6. \]

In $x$-axis all atom will be same line

\[ \text{APF} = \frac{1 \times \frac{4}{3} \pi r^3}{a^3} = 0.52. \]

Ex- Polonium, Flourstar, Mn.

(2) BCC

In case of BCC there are $\Theta$ atom at $\Theta$ corner of cube and one atom at the centre of unit cell.

No of atoms per unit cell = $8 \times \frac{1}{8} \times 1 = 2$
→ Co-ordination no. = 8

→ \[ \text{APF} = \frac{3 \times \frac{4}{3}\pi r^3}{a^3} = 6 \theta \]

\[ a\sqrt{3} = 4r \]

Ex- Li, Na, K, Cr, Fe (α-iron, 8-iron)

3) FCC →

In FCC there are 8 atom at corner of the cube and 6 atom at the centre of 6 faces of the cube.

No. of atom per unit cell = \[8 \times \frac{1}{8} + 6 \times \frac{1}{2} \]

= 4
Co-ordination no = 12

APF = \( \frac{4 \times \frac{4}{3} \pi r^3}{a^3} = \phi \)

= 0.74

\( \phi \) = Au, Ag, Cu, Ni, Pt, Pb

Fe (α-iron).

\underline{Note} - APF should be high.

Statement → FCC is also known as cubic closed packed (CCP).

14) Diamond Cubic → (Total 18 atom)

8 atoms at 8 corners of the cube

6 atoms at the centre of 6 faces of the cube

4 atoms are inside unit cell

→ No of atoms per unit cell

= \( 8 \times \frac{1}{8} + 6 \times \frac{1}{2} + 4 = 8 \)

Diamond cubic is the hexagonal structure

→ Co-ordination no = 4

\( \phi \) = 0.53

\( \theta \) = \( \frac{60\pi}{180} \)
This structure also called Zinc blende structure (Zns)

Group-3.5 Compound are having this type of structure

(5) Hexagonal - Closed packing (HCP):

APER = 0.74

Layer A

Layer B

Centre atom

No. of atom per unit cell = 3 + 2 \times \frac{1}{2} + 12 \times \frac{1}{6} = 6

Coordination no = 12

(6) Graphite:

Vander wall Weak bond
1. Graphite is having hexagonal crystal structure but it is not HCP as there are no centre atom available in the hexagonal.

2. Each C-atom has 4 valence electron. 3 of these valence electron are used in forming covalent bond with adjacent atom in this same layer. The 4th is free to wander over the surface of the layer making graphite and electrical conductor.

- Weak bonding forces within layer are called Van der Waals forces because these forces are weak the layers can easily slide past each other.
- The sliding of each other gives graphite its softness for writing and its lubricating property.

Ex: (HCP) — Be, Zn, Mg, Cd, Co

Comparison b/w diamond & Graphite —

<table>
<thead>
<tr>
<th></th>
<th>Diamond</th>
<th>Graphite</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Hard/Soft</td>
<td>Very hard</td>
<td>Soft</td>
</tr>
<tr>
<td>(2) Structure</td>
<td>Tetrahedral</td>
<td>hexagonal</td>
</tr>
<tr>
<td>(3) Elec. properties</td>
<td>Insulator</td>
<td>Conductor</td>
</tr>
<tr>
<td>(4) Thermal</td>
<td>Conductor</td>
<td>Insulator</td>
</tr>
<tr>
<td>(5) Transparency</td>
<td>transparent</td>
<td>Opaque</td>
</tr>
</tbody>
</table>
### Comparison of Crystal Structure

<table>
<thead>
<tr>
<th>No. of atoms/unit cell</th>
<th>Co-ordination</th>
<th>APF</th>
<th>Atomic Radii (Å)</th>
<th>Ex</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC</td>
<td>8</td>
<td>4</td>
<td>$\frac{0.53}{3}$</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>SC</td>
<td>1</td>
<td>6</td>
<td>52</td>
<td>Polonium, Fluorine, Mn</td>
</tr>
<tr>
<td>BCC</td>
<td>2</td>
<td>8</td>
<td>68</td>
<td>Li, Na, K, Cu, Fe (α, β)</td>
</tr>
<tr>
<td>FCC</td>
<td>4</td>
<td>12</td>
<td>74</td>
<td>Au, Ag, Ni, Cu, Al, Pt, Pb</td>
</tr>
<tr>
<td>HCP</td>
<td>6</td>
<td>12</td>
<td>74</td>
<td>Be, Zn, Mg, Cd, Co, G</td>
</tr>
</tbody>
</table>

\[ \frac{C}{a} = \frac{\text{Max dimension}}{\text{Min dimension}} = 1.63 \]

### Imperfections in Solid

- Point defect
- Line
- Surface
- Volume

There are two types of point defect:

1. **Vacancy**: A vacancy is a point defect which involves a missing atom within a crystal.
Schottky defect is a vacancy defect in which a pair of anion and cation is missing from the crystal structure. Ex: \( \text{Na}^+ \text{Cl}^- \) missing

2. Impurity defects:
   - Substitutional
   - Interstitial

1. Substitutional: This defect refers to a foreign atom which substitutes or replaces a parent atom in the crystal.

An interstitial impurity is a small sized atom occupying a wide space in the parent crystal.

\[
\begin{array}{c}
\text{foreign atom} \\
\text{Substitutional} \\
\end{array}
\]

\[
\begin{array}{c}
\text{foreign atom} \\
\text{Interstitial} \\
\end{array}
\]
1. In a crystal lattice the vacancy created by the absence of certain atoms are known as:
   (a) Heitz defect
   (b) Pauli's...
   (c) Crystal
   (d) Schottky

2. The crystal in which atoms are chemically highly inactive and they do not form compound with other atom.
   (a) Ionic crystal
   (b) Metal
   (c) Vander waals crystal
   (d) Valence crystal
   Crystal having covalent bond

3. Group-3,5 semiconductor compound have which one of the following crystal structure:
   (a) BCC
   (b) FCC
   (c) Hexagonal
   (d) Zinc Blende
When BCC iron is heated it changes to FCC iron resulting in:

(a) Increase in volume
(b) Contraction in volume
(c) No change in
(d) Crack in the material

density ↑

BCC → FCC

APF = 0.68
APF = 0.74

\[
\text{APF} = \frac{\text{Volume of unit cell}}{\text{Volume of unit cell}}
\]
Dielectric Properties of Material

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

Its main function of non-conducting material is charge storage. If it is called a dielectric.

Its main function of non-conducting material is to provide electrical insulation. Then it is called an insulator.

Parameters of dielectric →

→ Dielectric Constant (ε)
→ Dipole moment (μ)
→ Polarization (P)
→ Polarizability (α)

1) Dielectric Constant → It is defined as the ratio of electric flux density to electric field intensity.

\[ \varepsilon = \frac{D}{E} \]

Where, ε - Dielectric Constant

\[ = \varepsilon_0 \varepsilon_r \]

ε₀ - Permittivity of free space = 8.85 × 10⁻¹² F/m,
ε_r - Relative permittivity
(3) **Dipole-moment** → Two opposite charges separated by a distance constitute an electric dipole.

- Dipole moment is defined as the product of charge and distance of separation.
- It is the vector quantity, which is directed from negative to positive charge.

\[
\begin{array}{c}
+q \quad \vec{p} \quad -q \\
\end{array}
\]

Unit:
1. 1 **Coulomb-m.**
2. 1 **Debye.** = \(3.33 \times 10^{-30}\) Q·m.

**NOTE:** \( \vec{D} = \epsilon \vec{E} \)

- The above relation is applicable only to isotropic material (materials in which the dielectric and other physical properties are independent of the direction in which they are measured).
- Poly crystalline material with a random distribution of grains is non-directional (Isotropic).
- So above relation can be used for this material.
- Single crystal materials are anisotropic. So one can't use the above relation.
For anisotropic materials, the dielectric constant should be replaced by a **tensor** quantity in this formula.

\[ P = \frac{B}{\text{Volume}} \]

\[ N = \text{no. of dipoles per unit volume} \]

3) **Polarisation** → It is defined as dipole moment per unit volume.

\[ P = \frac{Qd}{V} \rightarrow \text{Q/m}^2 \]

\[ N \cdot P \]

Relation bw polarisation and electric field →

In dielectric material, bound charges are predominant under the application of an applied electric field.

The bound electron are displaced, the centroid of electron cloud is separated from the centroid of nucleus, the atom is said to be polarised.

This phenomenon is called electronic polarisation.

Let us consider a dielectric slab of thickness, \( d \), is placed in an electric field, \( E_0 \).
All the charges except at the boundary of dielectric.

Thus, the net result is the formation of surface charge at the top surface and \((-w)\) surface charge at the bottom surface.

\[
P = \frac{P}{\text{Vol.}} = \frac{Q \cdot d}{A \cdot ds} = \frac{P_b \cdot \Delta s}{\Delta s} = P_b
\]

The surface charge distribution produces secondary electric field \(E_s\)  
\[
\rightarrow E_s = \frac{P_b}{\varepsilon_0} \quad (\text{opposite to } P)
\]

Total electric field inside dielectric

\[
E = E_0 + E_s = E_0 - \frac{P_b}{\varepsilon_0}
\]

\[
E = E_0 - \frac{P}{\varepsilon_0}
\]

\[
\varepsilon_0 E = \varepsilon_0 E_0 - P
\]

\[
\varepsilon_0 E_0 = \varepsilon_0 E + P = D
\]
\[
D = \varepsilon_0 E + P \\
\varepsilon E = \varepsilon_0 E + P \\
\varepsilon_0 \varepsilon E = \varepsilon_0 E + P
\]

**Dielectric Strength & Dielectric breakdown**

In any material, the field intensity cannot be increased indefinitely.

⇒ When a high electric field is applied across a dielectric material, a considerable number of \( \varepsilon \) may get excited to the energy levels within the conduction band.

⇒ As a result, the current through the dielectric increases and cause localized melting, burning, and vaporization of dielectric material leading to irreversible degradable or even failure of material.

⇒ It results in high electrical conductivity and total loss of charge storage property of dielectric.

⇒ This phenomenon is called dielectric breakdown.

⇒ Dielectric strength represents the magnitude of applied electric field necessary to produce breakdown.

⇒ It is also defined as the maximum potential gradient that can withstand without being.
Which dielectric is subjected to electric field.

- Moisture, Contamination increased temp. and mechanical stress usually tends to decrease the dielectric strength.

**Mechanism of Polarization:**

→ Electronic/Induced polarization
→ Ionic/Molecular
→ Orientational
→ Space charge/Interfacial

1) Electronic/Induced polarization:

Electronic polarization result from the displacement of the centroid of negatively charge electron cloud relative to the centroid of positively charge nucleus in an atom by an applied electric field.

This type of polarization is found in the material in which there is no interaction between the atom or molecule.

**Ex - Inert Gases: (Gp-B)**

\[ Re = \text{electronic polarizability} = 4\pi\varepsilon_0\alpha R^3 \]

\[ \alpha_{\text{He}} < \alpha_{\text{Ne}} < \alpha_{\text{Ar}} < \alpha_{\text{Kr}} \]
Induced Polarization ---

\[ P_{\text{ind}} = N P_{\text{ind}} = N \alpha_e \varepsilon \]

\[ \varepsilon_0 \varepsilon_r \varepsilon = N \left( 4\pi \varepsilon_0 R^3 \right) \varepsilon \]

\[ \varepsilon_0 \left( \varepsilon - 1 \right) = N \left( 4\pi \varepsilon_0 R^3 \right) \]

\[ \varepsilon_1 = 1 + 4\pi NR^3 \]

Electronic polarization is independent of Temp.

Qwiz: The no of dipole in volume of 1 cubic m of hydrogen gas is \( 9.8 \times 10^{26} \) the radius of the hydrogen gas atom is \( 0.53 \text{Å} \) calculate \( \alpha_e, \varepsilon_1 \)

Solv:

\[ \varepsilon_1 = 1 + 4\pi NR^3 \]

\[ \varepsilon_1 = 1 + 4\pi \times 9.8 \times 10^{-26} \times (0.53 \times 10^{-10})^3 \]

\[ = 1.0018 \]

\[ \alpha_e = 4\pi \varepsilon_0 R^3 \]

\[ = 4\pi \times 8.85 \times 10^{-12} \times (0.53 \times 10^{-10})^3 \]

\[ = 1.66 \times 10^{-41} \text{ \text{f} - \text{m}^2} \]

2) Ionic Polarization: This type of polarization occurs in ionic material in which cations and anions get displaced.
in opposite direction.

i.e. Alkali halides (NaCl).

* Ionic polarizability measures the shift of ions relative to each other.
* Ionic polarization is also independent of temp.

\[
\begin{array}{c|c|c|c|c}
\text{Na}^+ & \text{Cl}^- & \text{Na}^+ & \text{Cl}^- \\
\text{Cl}^- & \text{K}^+ & \text{Cl}^- & \text{K}^+ \\
\text{K}^+ & \text{Na}^+ & \text{K}^+ & \text{Na}^+ \\
\text{Na}^+ & \text{Cl}^- & \text{Na}^+ & \text{Cl}^- \\
\end{array}
\]

\[
E = 0 \\
p = 0 \\
P = 0
\]

\[
E \neq 0 \\
p \neq 0 \\
P \neq 0
\]

\[P_{\text{ind}} = \alpha_i E \]

\[\text{Total Polarization } P = P_e + P_i = N (\alpha_e + \alpha_i) E\]

* For most of material the ionic polarizability is less than the electronic polarizability. In general
Orientational Polarization → This type of Polarization is found in the material having Partial Ionic bond or Covalent bond.

i.e. CH₃Cl, CO, NO, NO₂, H₂O, Nitrobenzena etc.

1st

\[ + \quad \rightarrow \quad - \quad \rightarrow \quad + \]

\[ A \quad B \quad A \]

\[ P = 0 \]

\[ \overline{F_x} = \overline{O} = \overline{C} = \overline{O} \]

\[ \text{CO₂} \]

2nd

\[ + \quad \rightarrow \quad - \quad \rightarrow \quad + \]

\[ B \quad A \quad A \]

\[ P \neq 0 \]

Dipole moment due to orientation of molecule is called permanent dipole moment.

\[ \overline{F_x} = \text{H₂O} \]

These materials causes permanent dipole moment even in the absence of external electric field. Orientational polarization is given by

\[ P_0 = \frac{N P P^2}{3 k T} E \]
Where $P_p$ - permanent dipole moment

$$P_0 = N \alpha_0 E$$

$$\alpha_0 = \frac{P_p^2}{3kT}$$

$\alpha_0 \propto \frac{1}{T}$

**NOTE**
Orientational Pol. is inversely proportional to temp and directly proportional to the square of the permanent dipole moment.

$E=0$  $\rightarrow$  $E$

**Total Polarization**

$$P = P_i + P_e + P_0$$

$$P = N \left[ \alpha_e + \alpha_i + \alpha_0 \right] E$$

$$E_0 (E_i - 1) E' = N \left[ \alpha_e + \alpha_i + \frac{P_p^2}{3kT} \right] E'$$

$$E_0 (E_i - 1) = N \left[ \alpha_e + \alpha_i + \frac{P_p^2}{3kT} \right]$$

$E_0 (E_i - 1)$

When $\frac{1}{T} = 0$
Space-charge/Interfacial Polarization:

In this type of polarization, the resultant of lattice vacancy or impurity center present in the dielectric.

The three modes of polarization discussed above all due to charge that are locally bound in the atoms or molecules in the structure of solids or liquids.

In addition some free charge carriers also exist that can migrate for some distance through dielectrics. Free charge carriers migrating through the crystal under the influence of electric field may be trapped by defects such as lattice vacancies or impurity centers.

The effect of this will be a localize accumulation of charges which will induce its image charge on the electrodes and gives rise to dipole moment. This type of polarization called space charge polarization.

Such materials having lattice vacancy are called 'multiphase material'.

The total polarization of multiphase material can be given by:

\[ P_T = P_e + P_i + P_o + P_s \]
In case of single phase material — 
\[ P_T = P_e + P_i + P_0 \]

Internal field in Solids: — In case of gases, we assume that the internal field is equal to the applied electric field and as long as the density of molecule is reasonably low, this is a good approximation.

Highly in solid & liquid the molecules & atom are so close together that the field seen by them is the result of the field due to dipoles and the external field. 

\[ E_i = E + \frac{P}{\varepsilon_0} \]

Where —
- \( E_i \) — internal field
- \( E \) — external field
- \( \varepsilon \) — internal field constant

\( \varepsilon \) is a unit less quantity and depend upon the structure.

For cubic structure \( \varepsilon = \frac{1}{3} \)

\[ E_i = E + \frac{P}{3\varepsilon_0} \]

Lorentz internal field.
Classification of solid on the basis of their dielectric behaviour →

1. Elemental dielectric Solid.
2. IOnic non-polar solid.

(1) Elemental dielectric Solid.— These are the solids which posses only electronic polarization. These solids consist of only single type of atom.
Ex: Ge, Si, diamond, S.

Measurement of dielectric constant for solids:—

\[ E_i = E + \frac{\gamma}{\varepsilon_0} P \quad (1) \]

\[ P = N \alpha e E_i \quad (II) \]

\[ P = N \alpha e \left[ E + \frac{\gamma}{\varepsilon_0} P \right] \]

\[ P = \frac{N \alpha e}{1 - \frac{N \alpha e \gamma}{\varepsilon_0}} E \]

\[ P = \varepsilon_0 \varepsilon_\infty E \]

\[ \frac{N \alpha e}{1 - \frac{N \alpha e \gamma}{\varepsilon_0}} E' = \varepsilon_0 \varepsilon_\infty E \]
\[ \epsilon_{r-1} = \frac{\frac{N\alpha e}{E_0}}{1 - \left(\frac{N\alpha e}{E_0}\right)\gamma} \]

\[ \epsilon_{r} = \frac{1 - (\gamma - 1) \left(\frac{N\alpha e}{E_0}\right)}{1 - \gamma \left(\frac{N\alpha e}{E_0}\right)} \]

Imp. for Conventional

C. M. Equation (Clapeyron–Mossotti eqn) — This eqn is applicable for

materials having cubical structure (having uniform internal field).

\[ \gamma = \frac{1}{3} \]

\[ \epsilon_{i} = \epsilon + \frac{P}{3\epsilon_0} \]

from eqn no. A

\[ \epsilon_{r-1} = \frac{\frac{N\alpha e}{E_0}}{1 - \frac{N\alpha e}{3\epsilon_0}} \]

\[ \epsilon_{r+2} = \frac{\frac{N\alpha e}{E_0}}{1 - \frac{N\alpha e}{3\epsilon_0}} + 3 \]

\[ \epsilon_{r+2} = \frac{3}{1 - \frac{N\alpha e}{3\epsilon_0}} \]

\[ \frac{\epsilon_{r-1}}{\epsilon_{r+2}} = \frac{\frac{N\alpha e}{3\epsilon_0}}{3} \]

Cm eqn
For gases state

\[ E_1 = 1 \]

\[ \frac{E_1 - 1}{\beta} = \frac{N \alpha e}{\beta \varepsilon_0} \]

\[ E_0 (E_1 - 1) = N \alpha e \]

\[ E_0 \chi e = N \alpha e \]

\[ \alpha e = \frac{E_0 \chi e}{N} \]

\[ \text{Maxwell relation} \rightarrow \]

Relation b/w refractive index and relative permittivity of dielectric -

\[ \eta = \frac{c}{\nu} = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = \frac{1}{(\frac{1}{\sqrt{\mu_0 \varepsilon_0}})} \]

\[ \eta = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \sqrt{\mu_1 \varepsilon_1 \varepsilon_0 \varepsilon_1} \]

\[ \eta = \sqrt{\mu_1 \varepsilon_1} \]

For dielectric \[ \mu_1 = 1 \]

\[ \varepsilon_1 = \eta^2 \]

Debye's generalization of CL eqn-

It is applicable only for gases state. For gases,
\[ N = \frac{Na \cdot P}{M} \]

- **M** - Molecular Weight (kg)
- **P** - Molecular density (kg/m³)

**Na** - Avogadro no.

\[ = 6.023 \times 10^{23} \]

\[ \rightarrow \frac{E_1 - 1}{E_1 + 2} = \frac{Na \alpha e}{3\varepsilon_0} \]

\[ = \left( \frac{Na \cdot P}{M} \right) \cdot \frac{\alpha e}{3\varepsilon_0} \]

\[ \frac{Na \cdot \alpha e}{3\varepsilon_0} = \frac{E_1 - 1}{E_1 + 2} \cdot \frac{M}{P} \]

**Lorentz-Lorentz Equation**

\[ E_1 = \eta^2 \]

\[ \frac{Na \cdot \alpha e}{3\varepsilon_0} = \frac{\eta^2 - 1}{\eta^2 + 2} \cdot \frac{M}{P} \]

This equation is applicable for gases having electronic polarization.

Ex- Inert Gases
(2) **Ionic Non-Polar Solid** → These are the solids which posses electronic as well as ionic polarization.

* Ex: Alkali halide

* They do not have permanent dipole moment

* Total Polarization

\[ P_T = P_e + P_i \]

\[ P = N(\alpha_e + \alpha_i) E \]

(3) **Polar Solid** → These are the solid which posses electronic, ionic as well as orientation polarization.

* These solid consist of dissimilar atoms having partial ionic bond.

* These solids posses permanent dipole moment

* Ex: Nitrobenzene, ortho & meta dichloro benzene

**Ortho - dichloro benzene**

Not symmetry. So permanent dipole.
Classification of dielectric on the basis of their dielectric behaviour in Electric field.

- Piezo-electric.
  - Charge generation by mechanical field & converse
- Pyro-electric
  - Charge generation by thermal field & converse
- Ferro-electric
  - Charge generation by electric field & converse
- Anti Ferro-electric

1. Piezo-electric material → Some material get polarized when they are subjected to a mechanical stress. Such material are called piezo-electric material. This property of material is called Piezo-electricity. When these material are subjected to an electric field, the material gets strained.

*The strain produced is proportional to the applied electric field.

\[ \text{Strain} \propto E \]

There are two types of effect in Piezo electricity:
(a) **Direct Effect** → Generation of electric charge from a mech. stress.

Application — Microphone. Gas lighter.

(b) **Inverse Effect** → Generation of strain due to applied electric field

App— Quartz Watches.

Examples of Piezo electric materials →

1. Quartz
2. Barium Titanate. (BaTiO₃)
3. Lead Titanate (PbTiO₃)
4. Lead Zirconate (PbZrO₃)
5. Potassium dihydrogen phosphate (KDP)
6. Ammonium dihydrogen phosphate (ADP)
7. lead zirconate titanate (PZT)
8. Rochelle Salt

Application of Piezo electric material →

1. Filter
2. Oscillators
3. Resonators
4. Ultra sonic flow detector
5. Quartz Watches
**Electrostriction**: Some material gets strain when they are subjected to an electric field but converse is not true.

*This property of material is called electrostriction.*

The strain produced in the material is proportional to the square of electric field.

\[ \text{Strain} \propto E^2 \]

**Expression for Voltage sensitivity of Piezo electric material**:

```
\[ \text{Mech. stress} = \frac{\text{F/A}}{\text{V}} \]
```

Produced charge:

\[ Q \propto F \]

\[ Q = d \cdot F \]

Where \( d \) = charge sensitivity

\[ \text{Unit} \rightarrow \text{ (Q/N)} \]

\[ CU = df \]

\[ V = \frac{df}{Q} \]
\[
\frac{d f}{c a} = (\frac{f}{a}) \cdot (\frac{d f}{c}) \cdot t
\]

\[
V = P \cdot \frac{d f}{c}
\]

Where \( q = \text{Volt Sensitivity} \)

\[
q = \frac{d f}{c} = \frac{V}{P \cdot t} = \frac{E}{P}
\]

Voltage Sensitivity \( \rightarrow \) It is defined as electric field produced per unit mech.

Stree.

Unit - \( q = \frac{V}{P \cdot t} = \frac{V}{(\frac{f}{a}) \cdot t} = \frac{V \cdot A}{f \cdot t} \)

\( V \text{- m/s} \).

Some Important Points \( \rightarrow \)

\( E_i \) \( \rightarrow \) \( P_c + P_i + P_o \)

\( P_c + P_i \)

\( \text{melting Pt.} \) \( \rightarrow \) \( \text{liquid} \)

\( \text{Solid} \) \( \rightarrow \) \( \text{liquid} \)

\( E_i \) vs. \( T \) Curve for Nitrobenzene.
1. Polar solids contain's permanent dipoles but these are frozen in the solid state and can no longer be aligned by the external field. Thus for polar solid one can measure only electronic and ionic polarization.

2. In liquid state dielectric constant decreases with increasing temp due to the fact that orientational polarization decreases with increases temp.

3. In solids dielectric constant is independent of temp. But in liquids and gases it decreases with increasing temp.

4. Spontaneous Polarization: Certain dielectrics exhibit the property of spontaneous polarization, i.e., it means non-zero polarization even in the absence of external electric field. 

Example: Ferroelectric material

Pyroelectric material

\[
P = N \alpha E_i \\
= N \alpha (E + \frac{\gamma}{E_0} P)
\]

\[
P = \frac{N \alpha E}{1 - \frac{N \alpha \gamma}{E_0}} = 0
\]

\[
\neq 0
\]

We want \( P \neq 0 \). So condition is \( \gamma E_0 = 0 \).

for spontaneous polarization

\( E = 0 \quad P \neq 0 \)
For this value of denominator should be zero

\[ 1 - \frac{N \alpha Y}{\varepsilon_0} = 0 \]

\[ \frac{N \alpha Y}{\varepsilon_0} = 1 \]

\[ A = N \alpha \] 

\[ P = \frac{N \alpha \varepsilon E}{1 - \frac{N \alpha Y}{\varepsilon_0}} \]

The above sys represents a closed loop system with (true) f.b having

\[ G_{\text{pin}} = N \alpha \]

f/b factor = \( \beta = \frac{Y}{\varepsilon_0} \)

For true f.b

\[ A \beta = 1 \]

\[ \frac{N \alpha Y}{\varepsilon_0} = 1 \]

Pyro electric material \( \rightarrow \) Polarization of material by

A change in material is called Pyro electricity.

*True one material which passes spontaneous Polarization
The direction of polarization cannot be reversed by reversing the direction of electric field.

* The polarization of these materials changes with change in temp.

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

\( \lambda \) - is negative quantity.

Ex: \( BaTiO_3 \) Tourmaline

Pyroelectricity is the ability of certain materials to generate a temporary voltage when they are heated or cooled.

* The change in temp. modifies the positions of the atoms in the crystal structure such that the polarization of material changes. This polarization change gives...
rise to a Voltage across the crystal. If the temp stays constant at its new value the Pyroelectric Voltage gradually disappears due to leakage Current.

It Pyro electricity should not be confused with thermo electricity.

In Pyro electricity the whole crystal is charged from one temp to another temp and result is temporary Voltage across the terminal Crystal.

In thermo electricity one side of material is kept at one temp and the other side is kept at different temp and result is generation of permanent Voltage across the crystal.

2) Ferroelectric material → Ferroelectric material shows the phenomenon of hysteresis these material exhibits spontaneous polarization even in the absence of external field.

The direction of polarization can be reverse by reversing the direction of electric field.

The ferroelectric material remain ferroelectric upto a critical temp called Curie temp and above Curie temp the material start behaving like piezoelectric material.
Hysteresis Curve

Residual Polarization
Or Remanent Polarization

* When a ferroelectric material is subjected to an external field, the material follows the path OA in the hysteresis curve. The material remains polarized even at the external field is reduced to zero.

* This residual value of polarization (O C) is called Residual or Remanent Polarization.

* To reduce the residual polarization to zero, an electric field is applied in the reverse direction. This field is called Coercive Field.

\[
\chi_e \propto \frac{T}{T - T_c} \quad (\text{Susceptibility } \chi_e).
\]

\[
\chi_e
\]

\[
\text{Curie - temp.}
\]

\[
\text{Ferro elec.}
\]

\[
\text{Piezo elec.}
\]
The electric susceptibility of the ferroelectric material increases with increase in temp whereas it decreases with increase in temp in case of Piezo electric material.

Above Curie temp

When temp is increase the area of hysteresis loop decreases and at critical temp called Curie temp hysteresis loop merges in two straight line.

For Piezo electric material.

Above Curie temp the relationship b/w Polarization and electric field is governed by Curie-Weiss law.

Curie-Weiss law → Above Curie temp the polarization in material can be assum to be

Orientalional polarization it means

\[ P_0 = \frac{N P_p^2}{3kT} E_i \]

\[ = \frac{N P_p^2}{3kT} \left[ E + \frac{y}{E_0} P_0 \right] \]
\[ P = \frac{\frac{N_b^2}{3KT} \cdot E}{1 - \frac{N_b^2}{3K} \cdot \frac{Y}{E_0}} \]

\[ = \frac{\frac{N_b^2}{3K} \cdot E}{T - \frac{N_b^2}{3K} \cdot \frac{Y}{E_0}} \]

\[ P = \frac{CE_0}{T - \Theta} \quad \text{Curie-Weiss law.} \]

Where

\[ \Theta = \text{Curie-temp.} \]

\[ = \frac{N_b^2}{3K} \cdot \frac{Y}{E_0} \]

\[ C = \frac{\Theta}{Y} = \text{Curie-const.} \]

\[ Y = \frac{\Theta}{C} = \text{internal field constant} \]

**Ex-1. Rochelle Salt**

2. BaTiO₃
3. PbTiO₃
4. Sodium Nitrate
5. KDP
6. Alums (फिल्म)

**Rochelle Salt**

\[ P \]

\[ 0.25 \text{ C/m}^2 \]

\[ -18°C \quad 23°C \]

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www.raghul.org
* Rochelle Salt is first available ever discovered ferroelectric material
* It has two Curie temp at (-18°C) & (23°C)
* Spontaneous polarization : 25 Ω/m²

![](image1.png)

* Curie temp is 123°C
* Spontaneous polarization is 4.95 Ω/m²

![](image2.png)

* BaTiO₃ is best known ferroelectric material
* Curie temp is 130°C
* Spontaneous polarization is 26 Ω/m²
* It has 6 possible direction of spontaneous Polarization.
* It have highest ionic Polarizibility because
*Titanium ion has charge of (+4) unit.
*It can be displaced over a relatively larger distance.

Ferroelectric domains

Ferroelectric materials.

Each ferroelectric material is divided into small regions. Each region is spontaneously polarized with uniform direction of polarization.

The direction of polarization varies from one region to another region. These regions are called ferroelectric domain.

The boundary separating the ferroelectric domain are known as domain walls.

When an external field is applied, the dipoles of all these regions get aligned along the external field, and domain wall collapse resulting in the increasing polarization.
The path (OAB) of hysteresis curve shows collapsing of domain walls & growth of single domain having all the dipoles in some direction.

Antiferro electric material

These are the material which posses zero spontaneous polarization.

The dipoles are alligned in anti parallel direction

These materials are anti ferro electric up to a critical temp called curve temp & above curve temp these starts behaving like piezo electric materials

Ex. Sodium Niobate, ADP, PbZrO3
* All ferroelectric materials are pyro as well as piezo electric.

* All pyro electric materials are piezo electric.

Para electric material $\rightarrow$ These materials possess zero spontaneous material.

They have dipole but are unaligned.

Under the influence of electric field, these dipole will align, resulting in the generation of polarization of the material.

Ex: Ceramic

\[ P \rightarrow E \]
Consider the following statement related to Piezo electric material and their effect.

1. Shear applied to the material produces electronica polarization.
2. An electric field applied to the material produces strain in it.
3. All Piezo electric materials are ferro electric material. Which of these statements are correct.

Consider the following statement...

In a ferro electric material:
1. All domains are lined in the direction of electric field giving rise to saturation polarization (spontaneous polarization).
2. If field is reduced to 0, many domains remain alligned.
3. The residual polarization can be eliminated only if material is heated above temp. (We can also with reverse electric field)

* Piezo electricity is the reverse effect of
  1. Peltier effect
  2. Hall effect
  3. Electro luminescence
  4. Electrostriction

**Q:** In a solid or liquid dielectric with externally applied electric field, as inter atomic distances increase the internal field.
1. Increases

2. Decreases

3. Remain unaltered

4. Increases or decrease based on temp.

\[ E_i = E + \frac{\gamma}{\varepsilon_0} P \]
\[ = E + \frac{\gamma}{\varepsilon_0} (N \alpha E_i) \]
\[ \downarrow E_i = \frac{E}{1 - \left(\frac{\gamma}{\varepsilon_0}\right)} \uparrow \]

**Question:** Consider a Parallel Plate Capacitor having an area of 6.45 \times 10^{-4} m^2 and a plate separation of 3 \times 10^{-3} m across, which a potential of 10 V is applied. If a material is having a dielectric constant of 6.0 is positioned within the region below the plates calculate:

(a) \( C \)

(b) \( Q \)

(c) \( D \)

(d) \( P \)

\[ C = \frac{\varepsilon_0 A}{d} \]
\[ = \frac{6 \times 6.45 \times 10^{-4} \times 3 \times 10^{-3}}{2} \]
\[ = 3 \times 6.45 \times 10^{-5} \]
\[ = 17.1 \text{ PF} \]

\[ Q = 17.1 \times 10^{-12} \times 10 \]
\[ = 17.1 \times 10^{11} \text{ Q} \]
D = \varepsilon E
= \varepsilon_0 \varepsilon_i \left( \frac{N}{d} \right)
= 8.85 \times 10^{-12} \times \frac{6 \times 10}{2 \times 10^{-3}}
= 2.66 \times 10^{-7} \text{ C/m}^2

P = \varepsilon_0 \chi E
= \varepsilon_0 (\varepsilon_i - 1) E
= 2.22 \times 10^{-7} \text{ C/m}^2

**Quest.** Calculate the voltage generated across the piezo electric material of thickness 1 cm when a mech. stress of 100 N/m² is applied.

(Given \( \varepsilon = \text{Vol. Sensitivity} = 23 \times 10^3 \text{ Vm/N} \))

\[ V = P \cdot \varepsilon \cdot \frac{1}{d} \]
\[ = 10 \times 23 \times 10^3 \times 10^{-12} \]
\[ = 2300 \text{ V} \]

**Quest.** The variation of the dielectric constant of C₆H₅N as a fun of temp. are plotted in the figure. Calculate the permanent dipole moment of molecules if no. of molecules per meter³ is 9.5 \times 10^{25}

\[ \chi = \varepsilon_0 (\varepsilon_i - 1) \]
\[ \varepsilon_0 (\varepsilon_i - 1) = N \left( \alpha_e + \alpha_i + \frac{P^2}{3kT} \right) \]
Slope = $\frac{Np^2}{3k\varepsilon_0}$

\[ p^2 = \frac{3 \times 6 \cdot 6 \varepsilon_0}{2.5 \times 10^{25}} \]

\[ = \frac{3 \times 6 \times 1.38 \times 10^{-23} \times 8.85 \times 10^{-12}}{2.5 \times 10^{25}} \]

\[ = 2.68 \times 10^{-30} \text{ Q-m} \]

Que: A homogeneous slab of lossless dielectric material is chosen by an electric susceptibility of 0.12 and carries a uniform electric flux density within it of 1.6 nC/m². Find electric field intensity, polarization, dipole moment if there are $2 \times 10^9$ dipoles/m³, the voltage between the equipotential 2.54 cm apart surface.

Sol:

\[ \chi_e = 0.12 \]

\[ D = 1.6 \text{ nC/m}^2 \]

\[ E = \frac{D}{\varepsilon_0} \]

\[ \varepsilon_0 \varepsilon_1 \]

\[ E = \frac{1.6 \times 10^{-9}}{8.85 \times 10^{-12} \times 1.12} \]

\[ = 161.4 \text{ V/m} \]

\[ P = \varepsilon_0 \chi_e E \]

\[ = 8.85 \times 10^{-12} \times 0.12 \times 161.4 \]

\[ = 1.71 \times 10^{-10} \text{ J/m}^2 \]
\[ p = \frac{P}{N} \]
\[ = \frac{1.71 \times 10^{10}}{8.55 \times 10^{19}} = 0.55 \times 10^{-9} \text{ C-m} \]

\[ U = \varepsilon_a d \]
\[ = 161.4 \times 2.54 \times 10^{-2} \]
\[ = 4.1 \text{ V} \]

**Dielectric in AC field** — When an AC field is applied, the dielectric constant which was real for static field, breaks into real and imaginary part.

\[ \varepsilon_r = \varepsilon'_r - j \varepsilon''_r \]

*Real part of dielectric constant decreases with increase in freq.*
*Imaginary part of dielectric constant 1st increase, attains a maximum value then decreases with increasing freq. At a lower freq. real part is dominant and at higher freq. imaginary part of dielectric constant is dominant.*
Dielectric loss:— The absorption of electrical energy by a dielectric material subjected to an a.c. field is known as dielectric loss. The result is in dissipation of electrical energy in the form of heat in the material.

It occurs due to two regions:

1. Oscillation of losses.
2. Continuous change in the orientation of dipole.

**Derivation of Energy loss:**

\[
\varepsilon_r = \varepsilon'_r - j \varepsilon''_r
\]

\[
D = \mathbf{\varepsilon} E(t)
= \varepsilon_0 \varepsilon_r \cos \omega t
= \text{Re} \left[ \varepsilon_0 \varepsilon_r e^{j\omega t} \right]
\]

\[
J = \text{Current density} = \frac{d}{dt} [D]
= \text{Re} \left[ \varepsilon_0 \varepsilon_r \varepsilon_0 \omega e^{j\omega t} \right]
\]

\[
J = \text{Re} \left[ \varepsilon_0 \varepsilon_r (\varepsilon'_r - j \varepsilon''_r) \varepsilon_0 \omega e^{j\omega t} \left( \cos \omega t + j \sin \omega t \right) \right]
\]

\[
= \varepsilon_0 \varepsilon_0 \omega \left[ \varepsilon''_r \cos \omega t - \varepsilon'_r \sin \omega t \right]
= \varepsilon_0 \varepsilon_0 \omega \varepsilon'_r \cos \omega t + \varepsilon_0 \varepsilon_0 \omega \varepsilon''_r \cos \left( \frac{\pi}{2} + \omega t \right)
\]

\[
J_1 = J_{1m} \cos \omega t \quad J_2 = J_{2m} \cos \left( \frac{\pi}{2} + \omega t \right)
\]

\[
\begin{align*}
J_1 & = J_{1m} \cos \omega t \\
J_2 & = J_{2m} \cos \left( \frac{\pi}{2} + \omega t \right)
\end{align*}
\]
\[ \delta - \text{loss angle} \]

\[ \tan \delta = \text{loss tangent} = \frac{J_{im}}{J_{2m}} = \frac{E_0 E_0' \omega \epsilon''}{E_0 E_0 \epsilon'} \]

\[ \tan \delta = \frac{\epsilon''}{\epsilon'} \]

\[ \text{Obj: for most of the dielectric materials} \]

\[ 0.001 \leq \tan \delta \leq 1.001 \]

\[ \text{Loss factor} - \epsilon' = \epsilon' \tan \delta = \epsilon'' \]

\[ \text{Power absorbed per unit volume in one time period} - \]

\[ W = \frac{1}{3 \pi} \int_{0}^{2\pi} f(t) \cdot d(\omega t) \]

\[ = \frac{1}{3 \pi} \int_{0}^{2\pi} E_0 \cos \omega t \cdot E_0 E_0' \omega (E'' \cos \omega t - E' \sin \omega t) d\omega t \]

\[ W = \frac{1}{3 \pi} E_0 E_0' \omega \left[ \int_{0}^{2\pi} \left( E'' \cos \omega t - E' \cos \omega t \cdot \sin \omega t \right) d\omega t \right] \]

\[ \left( \frac{1 - \cos 2\omega t}{2} \right) \]

\[ W = \frac{1}{3 \pi} E_0 E_0' \omega \cdot \frac{\epsilon''}{2} \cdot 2\pi \]
\[ W = \frac{1}{2} \epsilon_0 E_0^2 \omega E'' \, \text{Watt/m}^3 \]

\[ W \propto E'' \quad \propto \omega \quad \propto E_0^2 \]

Energy absorbed by dielectric from a.c. field is proportional to imaginary part of dielectric constant.

Loss Calculation using circuit analysis:

\[ P_L = V \cdot \frac{i_2}{\cos \delta} \cdot \sin \delta \]

\[ = V \cdot i_2 \cdot \tan \delta \]
\[ P_L = U \cdot i_c \cdot \tan \delta \]
\[ = U \left( \frac{V}{X_c} \right) \cdot \tan \delta \]
\[ P_L = U^2 \cdot \tan \delta \cdot \pi \cdot f \cdot C \rightarrow \text{Watt} \]
\[ = (E_0 d)^2 \cdot \frac{\pi \cdot f \cdot (E_0 \cdot A)}{d} \cdot \tan \delta \]
\[ P_L = E_0^2 \cdot \pi \cdot f \cdot E \cdot \tan \delta \]
\[ \frac{P_L}{Ad} = \frac{E_0^2 \cdot \pi \cdot f \cdot E \cdot \tan \delta}{\left( \frac{1}{\pi \cdot f \cdot E_0} \right)} \text{Watt/m}^3 \]
\[ \frac{P_L}{Vol.} = \frac{E_0^2 \cdot f \cdot E \cdot \tan \delta}{1.8 \times 10^{12}} \text{Watt/Cm}^3 \]

**Que:** A Solid specimen of dielectric has \( E_\text{r} = 4.2 \) and \( \tan \delta = 0.001 \) at 50Hz. If it is subjected to an electrical stress of 50kV/Cm. What is the heat generated in the specimen due to dielectric stress?

10) 291 W/Cm\(^3\)  (b) 5.82 MW/Cm\(^3\)
(c) 19.5 W/Cm\(^3\)  (d) 29.1 MW/Cm\(^3\)
Consider the following statement regarding an insulator material connected to a.c. voltage.

1. The dielectric constant increases with frequency.
2. Atomic polarization
   \[ \rightarrow \alpha = \frac{e_0 \varepsilon_e}{N_1} = \frac{e_0 (\varepsilon - 1)}{N_1} \]
   \[ \downarrow P = N_0 \alpha \]

**NOTE:** Dielectric constant of solid dielectric in the a.c. field is maximum at power freq. and decreases to unity at freq. in ultra violet range.

Consider the following statement:

3. The dielectric constant of an insulator depends on:
   1. Applied voltage
   2. Freq. of a.c. field
   3. Temp. \[ \alpha = \frac{e_0 \varepsilon_e}{N_1} = \frac{e_0 (\varepsilon - 1)}{N_1} \] \[ \Box = \frac{P_0}{3kT} \]
   4. Max. current density in insulator

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**Effect of Frequency on Polarization:**

1. Space charge polarization is effective up to power audio freq. (100 Hz)
   \[ S \cdot C \cdot Pol. < 100 \text{ Hz} \]
2. Orientation polarization is effective up to \(10^6\) to \(10^{10}\) Hz.
1. Ionic Polarization is effective up to infrared range \((10^{14} \text{ Hz})\).

2. Electronic Polarization is effective up to visible range \((5 \times 10^{14} \text{ Hz})\).

Equation governing motion of \(\varepsilon\) in A.C field →

\[ M \frac{d^2x}{dt^2} + 2\beta \frac{dx}{dt} + ax = -eE_0 \cos \omega t \]

Where -

\(- m\) - mass of \(\varepsilon\) cloud

\(- 2\beta\) - damping constant

\(- a\) - spring or force constant

\(E_0 \cos \omega t = \text{A.C field}\)

\(\omega_0 = \text{Resonant freq.} = \sqrt{\frac{a}{m}}\)

Quartz →

- Quartz is a crystalline material
- Structure is silicate tetrahedral \((\text{SiO}_4)\)
- Quality factor is in the range of \(10^4\) to \(10^6\)
- It has a shape of hexagonal prism with pyramids attached to both ends.
\[ \text{SiO}_4 \text{ (Silicate)} \]

\[ \text{AT (Temp Compensated Cut)} \]

\[ 35^\circ \]

\[ 48^\circ \text{ - BT (high freq. cut).} \]

\[ \text{AT Cut} \rightarrow \text{Thin plate making an angle of } 35\text{--}25^\circ \text{ with } z \text{ axis.} \]

\[ \star \text{ It is most widely used cut.} \]

\[ \star \text{ high degree of freq. stability over wide temp. range} \]

\[ \star \text{ Sensitive to stress} \]

\[ \text{BT Cut Crystal} \rightarrow \]

\[ \star \text{ It has poorer temp. char. than AT Cut.} \]

\[ \star \text{ It can be used for crystals having higher freq. than AT Cut.} \]

\[ \text{Stress Compensated Cut} \rightarrow \text{(SC)} \]

\[ \text{In highly stable oscillator Ckt AT cut quartz crystal are generally employed. What is the region for using this particular orientation?} \]

\[ \text{Quartz crystal has a natural growth along this plane. The corresponding quality factor is largest for this orientation.} \]
An AT cut crystal can be used over a wide range.

There is minimal temp variation of freq.

The resonance freq. of a quartz crystal oscillator shows least variation with temp. when the orientation of the crystal is:

1. X cut
2. Y cut
3. NT cut
4. AT cut

**Equivalent circuit diagram of quartz crystal:**

![Equivalent circuit diagram of quartz crystal]

Where:
- \( R_s \) - represents damping constant.
- \( L_s \) - mass of crystal.
- \( C_s \) - spring constant.
- \( C_p \) - electrostatic capacitance between opposite faces of crystal.
\[ Z_s = R_s + j \left( \omega L_s - \frac{1}{\omega C_s} \right) \]
\[ Z_P = \frac{1}{j \omega C_P} \]
\[ Y = \frac{1}{Z_s} \frac{1}{Z_P} \]
\[ = \frac{1}{R_s + j (\omega L_s - \frac{1}{\omega C_s})} + j \omega C_P \]
\[ = \frac{R_s - j (\omega L_s - \frac{1}{\omega C_s})}{R_s^2 + (\omega L_s - \frac{1}{\omega C_s})^2} + j \omega C_P \]
\[ Y = Y_{\text{real}} + Y_{\text{imag}} \]
\[ = \frac{R_s}{R_s^2 + (\omega L_s - \frac{1}{\omega C_s})^2} + j \left[ \omega C_P - \frac{(\omega L_s - \frac{1}{\omega C_s})}{R_s^2 + (\omega L_s - \frac{1}{\omega C_s})^2} \right] \]

**For resonance:**
\[ Y_{\text{imag}} = 0 \]
\[ \omega C_P - \frac{(\omega L_s - \frac{1}{\omega C_s})}{R_s^2 + (\omega L_s - \frac{1}{\omega C_s})^2} = 0 \]
\[ \omega C_P \left[ R_s^2 + (\omega L_s - \frac{1}{\omega C_s})^2 \right] - (\omega L_s - \frac{1}{\omega C_s}) = 0 \]

**For higher amplitude of Oscillator**
\[ R_s = 0 \]
\[ \omega C_P \left[ (\omega L_s - \frac{1}{\omega C_s}) - 1 \right] \left[ \omega L_s - \frac{1}{\omega C_s} \right] = 0 \]
\[(\omega_l - \frac{1}{\omega_c}) = 0 \quad \text{or} \quad \frac{1}{\omega_c} = \omega_l \quad \cdots \quad (1)\]

**For series resonance** —

\[
Y_s = Y_{\text{real} \mid \text{max}} = \frac{Rs}{Rs^2 + (\omega_l - \frac{1}{\omega_c})^2} \quad \rightarrow \quad \text{min.}
\]

\[
Y_s = \frac{1}{Rs}
\]

\[
\omega_s = \frac{1}{\sqrt{LsC_s}}
\]

**For parallel resonance** —

\[
Y_p = Y_{\text{real} \mid \text{min}} = \frac{Rs}{Rs^2 + (\frac{1}{\omega_pC_p})^2} \quad \frac{1}{\omega_pC_p}
\]

\[
\omega_pLs - \frac{1}{\omega_pC_s} = \frac{1}{\omega_pC_p}
\]

\[
\omega_p = \frac{1}{\sqrt{LsC_s}}
\]

Where

\[
C^1 = \frac{CsC_p}{Cs + C_p}
\]
Relation between $\omega_s$ and $\omega_p$:

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

"$|z|$" vs $\omega$ Curve:

1. $\omega_p > \omega_s$.
2. When $\omega < \omega_s \rightarrow$ CRT is capacitive.
3. $\omega_s < \omega < \omega_p \rightarrow$ inductive.
4. $\omega > \omega_p \rightarrow$ capacitive.

→ Reactance vs $\omega$ curve:

Question:

A Quartz Crystal has the following characteristics:

→ Series resonance freq. = 200kHz.
→ Impedance at series resonance = $\infty$.
→ Parallel resonance freq. = 200.25 kHz.
Impedence of Parallel resonance = 40MΩ

determine the component values?

\[ P = 200\text{KHz} \Rightarrow \omega_c = 2\pi \times 200 \times 10^3 \]
\[ R_s = 200\Omega \]
\[ L_P = 200.25\text{KHz} \]
\[ B_P = 40\text{MΩ} \]

\[ \omega_s = \frac{1}{\sqrt{L_s C_s}} \]
\[ 200 \times 10^3 = \frac{1}{\sqrt{L_s C_s}} \]  \hspace{1cm} (1)

\[ \omega_p = \frac{C_s C_p}{\sqrt{L_s \left( \frac{C_s C_p}{C_s + C_p} \right)}} \]  \hspace{1cm} (11)

\[ \frac{1}{40 \times 10^6} = \frac{2 \pi \times 200}{(200)^2 + \left( \frac{1}{200.25 \times C_p} \right)^2} \]

\[ \left( \frac{1}{200.25 \times C_p} \right)^2 = \]

\[ C_p = \]

\[ Z_P = \frac{R_s^2 + \left( \frac{1}{\omega_p C_p} \right)^2}{R_s} \]  \hspace{1cm} (11)

\[ \omega_p = \omega_s \sqrt{1 + \frac{C_s}{C_p}} \]  \hspace{1cm} (11)

From (11) \[ C_p = 8.08\text{PF} \]

From (11) \[ C_s = 0.022\text{PF} \]

\[ L_s = 28.48\text{H} \]
Consider the following statement related to Quartz crystal.

(a) Quartz displays ferroelectric behaviour.
(b) Quartz is used in electronic oscillator circuit.
(c) Quartz crystal is formed by repeating silicate tetrahedrons which are correct.

Effective quality factor of the equivalent electrical circuit of quartz crystal is of the order of:

(a) 20  (b) 200  (c) 2000  (d) 200,000

\(10^4 - 10^6\)
Magnetic Properties of materials

Permeability
Magnetic dipole moment
Magnetization

**Permeability**

It is defined as the ratio of mag. flux density and mag. field intensity.

\[ \mu = \frac{B}{H} \]

Where:
- \( B \) - mag. flux density \( (\text{Wb/m}^2) \)
- \( H \) - mag. field intensity \( (\text{A/m}) \)

\[ \mu = \mu_0 \mu_r \]

Where
- \( \mu_0 = 4\pi \times 10^{-7} \text{ H/m} \)
- \( \mu_r \) - relative permeability
- \( \mu_0 \) - Permeability in free space

(2) **Magnetic dipole moment** → A current loop constitutes a mag. dipole.

Mag. dipole moment is defined as the product of the area of loop and current through the loop.
It is a vector quantity and its direction is normal to the plane containing current loop. 

\[ \mathbf{l} = i \times A \hat{n} \]

\( \hat{n} \) - unit vector along normal to the plane.

Unit - A·m²

Bohr Magnetron \rightarrow Atomic unit of magnetic dipole moment is called **Bohr magnetron**.

Let us consider an electron revolving around a nucleus in a circular orbit. The current through the loop is

\[ i = \frac{Q}{T} \]

\[ i = \frac{e}{\omega} \]

\[ i = \frac{e \omega}{2\pi} \]

\[ \text{Mag. dipole moment} \]

\[ \mathbf{p}_B = iA \]

\[ \mathbf{p}_B = \frac{e \omega}{2\pi} \times \pi r^2 \]

\[ \mathbf{p}_B = \frac{e \omega r^2}{2} \]

By Bohr’s hypothesis
Angular momentum

\[ m \nu = \frac{nh}{\pi} \]

Where \( h = \text{Plank's constant} = 6.623 \times 10^{-34} \text{ J} \cdot \text{s} \)

\[ m(\omega t) r = \frac{nh}{\pi \mu} \]

\[ \omega = \frac{nh}{\pi \mu m r^2} \]

From eq\(^9\)

\[ P_B = \frac{e r^2}{2} \left( \frac{nh}{3\pi \mu m^2} \right) \]

\[ P_B = \frac{nceh}{4\pi m} \]

1 \( \text{M}_B = \text{Bohr magneton} = \frac{eh}{4\pi m} \]

\[ = \frac{1.6 \times 10^{-9} \times 6.626 \times 10^{-34}}{4\pi \times 9.1 \times 10^{-31}} \]

\[ 1 \text{M}_B = 9.27 \times 10^{-24} \text{ A} \cdot \text{m}^2 \]

Larmor's angular freq.:

When \( B=0 \)

\[ \omega = \omega_0 = \frac{nh}{\pi \mu m r^2} \]

\( B \neq 0 \)

\[ \omega = \omega_0 + \omega_{\perp} \]

Larmor's angular freq.
\[ \omega_L = \frac{eB}{\gamma m} \]

It is defined as the change in angular freq. of orbital \( \varepsilon \) when an external mag. field is applied.

**Magnetization** : \( \mathbf{M} \) It is defined as magnetic moment per unit volume.

\[ \mathbf{M} = \frac{\mathbf{P_B}}{\text{Volume}} \]

\[ \mathbf{M} = N \mathbf{P_B} \]

Where \( N \) - no. of dipole per unit vol.

unit - \( A/m \).

The magnetic flux density inside a magnetic material under the influence of external field has two components:

* One component because of magnetisation
* Other two because of external field.

\[ B = \mu_0 H + \mu_0 M \rightarrow \mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P} \]

\[ B = \mu_0 (H + M) \]

\[ \varepsilon_0 \mu_0 H = \varepsilon_0 (H + M) \]

\[ M = (\mu_r - 1)H \rightarrow \mathbf{P} = \varepsilon_0 (\mu_r - 1) \mathbf{E} \]

\[ \mathbf{M} = \chi_m H \rightarrow \mathbf{P} = \varepsilon_0 \chi_e \mathbf{E} \]

Where \( \chi_m \) - Mag. Susceptibility.
Where \( X_m = \mu_r - 1 \)

\[
= \begin{cases} 
+ve, \text{ material will be attracted by mag. field.} \\
-ve, \text{ material will be repelled by mag. field.}
\end{cases}
\]

**Q:** Find the magnitude of the magnetic flux density in a material.

1. The magnetization is 2.8 A/m, magnetic susceptibility is 0.0025.
2. The magnetic field intensity is 1300 A/m, \( \mu_r = 1.006 \).
3. There are \( 8.2 \times 10^{28} \) atom/m\(^3\), each having a dipole moment of \( 3 \times 10^{-30} \) A·m\(^2\) in the same direction.

\[
X_m = 2 \times 10^{-4}
\]

So,

\[
B = \mu_0 H + \mu_0 M
\]

\[
= (4\pi \times 10^{-7} \times 1120) + (4\pi \times 10^{-7} \times 1.006)
\]

\[
= 1.411 \times 10^{-3} \text{ Wb/m}^2
\]

\[
H = 1300 \text{ A/m, } \mu_r = 1.006
\]

\[
B = \mu_0 \mu_r H
\]

\[
= 1.64 \times 10^{-3} \text{ Wb/m}^2
\]

\[
N = 8.2 \times 10^{28}, \quad \rho_B = 3 \times 10^{-30} \text{ A·m}^2, \quad X_m = 2 \times 10^{-4}
\]

\[
M = N \rho_B = X_m = 0.246 \text{ A/m}
\]
\[ B = \mu_0 M \cdot H \]
\[ = \mu_0 (x_m + 1) \left( \frac{M}{x_m} \right) \]
\[ = 1.54 \times 10^{-3} \text{ Wb/m}^2 \]

* **Origin of permanent magnetic dipole moment in materials**

* When ever a charge particle has an angular momentum, the particle will contribute to permanent dipole moment.

* In general there are three contributions to the angular momentum of an atom.

  1. **Orbital angular momentum of an \( \varepsilon \)**
     - It is due to orbital motion of \( \varepsilon \)
  2. **Electron spin angular momentum**
     - It is due to self spin of \( \varepsilon \)
  3. **Nuclear spin angular momentum**
     - It is due to nuclear spin.

* Magnetic properties of material are only affected by electron spin dipole moment (angular momentum).

* **Electron spin angular momentum**
  - Since \( \varepsilon \) has no charge, so its spin produces a magnetic dipole moment.

* The atoms having completely filled inner shells have 0 resultant spin dipole moment.
A group of elements having incompletely filled 3d state is known as transition group.

\[
\text{Ex- Atomic No-} \quad 19 \quad 28 \\
\text{K} \quad \text{Ni}
\]

1 Bohr magnetron = \( \frac{\text{\( \varepsilon \)h}}{4\pi m} \)

= \( \pm \frac{\text{\( \varepsilon \)h}}{4\pi m} \) (due to opposite spins of \( \varepsilon \))

<table>
<thead>
<tr>
<th>Atomic No.</th>
<th>Element</th>
<th>( \bar{\varepsilon} ) in 3-d state</th>
<th>( B_B ) (Mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>Ca</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>21</td>
<td>Sc</td>
<td>1</td>
<td>Mb</td>
</tr>
<tr>
<td>22</td>
<td>Ti</td>
<td>2</td>
<td>2 Mb</td>
</tr>
<tr>
<td>23</td>
<td>V</td>
<td>3</td>
<td>3 Mb</td>
</tr>
<tr>
<td>24</td>
<td>Cr</td>
<td>4</td>
<td>4 Mb</td>
</tr>
<tr>
<td>25</td>
<td>Mn</td>
<td>5</td>
<td>5 Mb</td>
</tr>
<tr>
<td>26</td>
<td>Fe</td>
<td>6</td>
<td>(10-6) = 4 Mb</td>
</tr>
<tr>
<td>27</td>
<td>Co</td>
<td>7</td>
<td>(10-7) = 3 Mb</td>
</tr>
<tr>
<td>28</td>
<td>Ni</td>
<td>8</td>
<td>(10-8) = 2 Mb</td>
</tr>
<tr>
<td>29</td>
<td>Cu</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>
\[
\begin{align*}
E_x &= Fe^{2+} \rightarrow 1s^2 \ 2s^2 \ 2p^6 \ 3s^2 \ 3p^6 \ 3d^6 \\
&\rightarrow 4m_B
\end{align*}
\]

\[
\begin{align*}
Fe^{3+} &= 1s^2 \ 2s^2 \ 2p^6 \ 3s^2 \ 3p^6 \ 3d^5 \\
&\rightarrow 5m_B
\end{align*}
\]

The magnetic moment in units of Bohr magnetron of an iron ion in any ferrite is:

(a) 0  
(b) 2  
(c) 4  
(d) 6

The outermost electronic configuration of a cobalt atom is:

(a) 3d^7 4s^2  
(b) 3d^6

\[\text{Classification of magnetic properties} \rightarrow\]

\[\rightarrow \text{Diamagnetic material}\]
\[\rightarrow \text{Paramagnetic material}\]
\[\rightarrow \text{Ferromagnetic}\]
\[\rightarrow \text{Antiferromagnetic}\]
\[\rightarrow \text{Ferri magnetic}\]

(1) Diamagnetic material \[\rightarrow \text{These materials have small & negative magnetic susceptibility.}\]

*These materials are repelled by applied magnetic field.
The magnetic flux inside diamagnetic material is

\[ \mathbf{B} = 0 \]

\[ \mu_0 (H + M) = 0 \]

\[ M = -H \]

\[ \frac{M}{\chi_m H} = \mu_1 e^{-1} \]

\[ \chi_m = -1 \]

\[ \mu_1 = 0 \]

The above relation \( \mu_1 = 0 \) all the perfect diamagnetism is one of the necessary conditions for a material to be a superconductor.

Magnetic susceptibility of these materials is independent of temperature.

Ex: Sulfur, diamond, NaCl, Al₂O₃, Cu, Au (Gold) etc.
Paramagnetic material → When these material is placed in an external magnetic field, a weak magnetisation in the same direction of magnetic field.

These materials have small positive value of magnetic susceptibility.

In Paramagnetic material permanent dipole moment of the atoms and ions has no mutual interaction, however in the presence of field the mag. moment have a tendency to turn towards the direction of applied field.

If no opposing force act, complete allignment of the dipole will be produced and the specimen would acquire a very large magnetisation, but thermal agitations of atoms opposes this tendency and tends to keep the dipole moment at dead random.

This result only a partial allignment in the field direction. Therefore a weak magnetisation and small positive value of suscepibility. The effect of increase the temp. is to increase the thermal agitation & therefore decrease the susceptibility.
The magnetization is governed by a law called Curie-law.

\[ M = \frac{N \beta_B^2}{x} H \]

\[ M = \frac{C}{T} H \quad \text{Curie law} \]

\[ M = x_m H \]

\[ x_m = \frac{C}{T} \]

\[ C = \frac{N \beta_B^2}{K} \]

Curie Constant

Some paramagnetic materials follow Curie-Weiss Law.

\[ M = \frac{N \beta_B^2}{KT} H_i \]

\[ H_i = H + \gamma M \]

\[ M = \frac{N \beta_B^2}{KT} [H + \gamma M] \]

\[ M = \frac{N \beta_B^2}{KT} \frac{H}{1 - \frac{N \beta_B^2}{KT} \gamma} \]

\[ M = \frac{N \beta_B^2}{1 - \frac{N \beta_B^2}{KT} \gamma} H \]
\[ M = \frac{C}{T-\Theta} H \]
\[ P = \frac{C\varepsilon_0}{T-\Theta} E \]

Where \( C = \frac{N_B P^2}{K} \)  - Curie Const.

\( \Theta = \text{Curie-temp.} = \frac{N_B P^2}{K} \gamma \)

\( \gamma = \text{internal field const.} = \frac{\Theta}{c} \)

\( X_m \uparrow \)

\[ \leftarrow \text{Ferro magnetic material} \quad \rightarrow \text{Paramagnetic material} \]

\[ \text{Ex- } \text{FeSO}_4, \text{MnSO}_4, \text{NiSO}_4, \text{Fe}_2\text{O}_3 \text{ etc} \]

\underline{Ferromagnetic Material} \rightarrow \text{These are the material which get magnetise in the direction of external field and remain magnetise even after the removal of mag. field. This property of ferromagnetic material is called spontaneous magnetization.}

A direction of magnetization can be reverse by reversing the direction of external mag. field.
* The ferro mag. material are characterised by parallel alignment of magnetic dipole.

\[ B = 0 \]

* When a magnetic field applied to a ferro mag. material, the material follows the path one in the hysteresis curve.

* When the mag. curve is reduce to zero, the non zero value of magnetization is called residual magnetisation.

* To reduce the magnetization to zero an external
Field is required to be applied in opposite direction known as coercive field. The material never comes back to its original state once exposed to external field.

The ferromagnetic material remain ferromagnetic up to a critical temp called Curie temp. These materials start behaving like paramagnetic material.

Above Curie temp hysteresis loop merges to a straight line.

\[
\begin{align*}
T &> \theta \\
\frac{B_{im}}{H} &> 0
\end{align*}
\]

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

<table>
<thead>
<tr>
<th>Material</th>
<th>Curie Temp (°K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co</td>
<td>1404</td>
</tr>
<tr>
<td>Fe</td>
<td>1043</td>
</tr>
<tr>
<td>Ni</td>
<td>631</td>
</tr>
<tr>
<td>Gd</td>
<td>289</td>
</tr>
</tbody>
</table>
Anti-ferro magnetic material →

The dipole moment in these material are alligned in antiparallel direction.

\[
\begin{align*}
\text{Antiferro mag} & \quad B = 0 \\
\end{align*}
\]

Net magnetisation is 0 when no external field is applied. But when material is subjected to an external field, the dipole moment start alligned in the direction of field.

These materials have small + (ve) values of susceptibility.

These material are anti-ferro magnetic up to a critical temp called Neel temp.

And above this temp, these material start behaving like Paramagnetic. And magnetization is governed by a law is similar to Curie-Weiss law, which is given by:

\[X_m = \frac{C}{T-(1-\Theta)}\]
Where \( \theta = \text{Neel temp} \)

\[
\theta = -\frac{Np_B^2}{K} \\
\theta = \frac{Np_B^2}{K} (-\gamma)
\]

\[
H_i = H - \gamma M.
\]

It means internal magnetisation is opposite to applied mag. field

\( X_m \) vs \( T \)

Ex- \( \text{MnO}_2, \text{MnO}, \text{FeO}, \text{CoO} \) etc.

(4) Ferri magnetic material → In ferri magnetic material dipole moment of adjacent atom are also aligned in opposite direction but they are not equal in strength.
These materials remain ferromagnetic up to a critical temperature called Curie temperature and above this temperature this material start behaving like paramagnetic.

The advantage of these materials is high d.c. resistivity as compared to ferromagnetic material.

Because of this property at current losses in ferrite are lesser than ferromagnetic material and because of this region ferrites are preferred for the construction of core of high freq. transformer.

Electrical & Magnetic characteristics of ferrite:

1. High d.c. resistivity
2. Low eddy current losses
3) High permeability
4) High dielectric constant
5) High Curie temp.

Application of ferrites:

- Hard
- Soft
- Rectangular
- Microwave

Soft and hard ferrites - These are ferrites which is used for construction of core of inductors and transformer.

* These materials have high permeability, low coercive force and low eddy current losses.

Ex- Mn + Zn ferrites.

Ni - Zn ferrites (audio + TV transformer)

Hard ferrites: - These are the ferrites which are used for construction of permanent magnets.

* These material have high permeability
* High coercive force
* High resistivity

Ex- Bo + Sr ferrites.
Rectangular ferrites \rightarrow These ferrites are having rectangular shape of hysteresis curve.

These ferrites are used as the core of magnetic memories.

- Mn-Mg ferrites.
- Ni-Li "
- Mn-Cu "

Microwave ferrites \rightarrow These ferrites is used at microwave frequency.

At these freq, the electro magnetic wave interact with the spin magnetic moment of e because of this, the plane of polarization of electromagnetic field gets rotated by some angle. When the wave passes through the material, this phenomenon is called Faraday rotation.

These ferrites is used in microwave devices
- Gyrotrons, Circulators & Isolators etc.

- of microwave ferrites-
  - Mn - ferrites
(a) Co - ferrites
(b) Ni - ferrites
(c) Garnets (YIG - Yttrium - iron - garnet) → used in magnetic bubble memory

Ferrites from magnetite → Mo Fe₂O₃
Where M = bivalent element
Ex: Cu, Zn, Co, Ni etc.

Ferrites from Garnets:
3 M₂O₃ · 5 Fe₂O₃
These are called "rare earth ferrites"

Ferrites can be considered as mixed oxide of metals A + B having inverse spinel structure; their formula can be written as:
(a) AB₂O₄
(b) A₂BO₂
(c) A₂B₂O₆

Magnetic Anisotropy: In single crystal material such as iron, the magnetic properties of material depend on the direction in which they are measured. This property of material is called magnetic anisotropy.
The one of the three methods to induce anisotropy is:

- Cold Working
- Magnetic Annealing
- Magnetic Quenching

**Cold Working** — Such as cold rolling, induced the uniaxial magnetic anisotropy in the direction of rolling.

**Magnetic Annealing** — In this process, heat treatment is done in the presence of a magnetic field in order to induce magnetic anisotropy.

**Magnetic Quenching** — In this process, the material is cooled down to Curie temperature in the presence of magnetic field. This magnetic quenching induces the magnetic anisotropy either in the direction of the field or perpendicular to the field.

**Magnetostriction** — When a material (magnetic material) is magnetized, changes in dimension are generally observed; this property of magnetic material is called magnetostriction.
There are three types of magnetostriction.

- **Longitudinal**: When change in the dimension is in the direction of applied field.
- **Transverse**: When change in the dimension is perpendicular to applied field.
- **Volume**: When change in the dimension is as well as parallel to applied field.

Some important points:

1. Magnetostriction is responsible for humming noise in the core of T/F.
2. Magnetostriction is caused by rotation of domain of ferromagnetic material under the influence of applied magnetic field.
3. (True) Magnetostriction material expands with increase in the strength of applied magnetic field and it contracts when strength decreases. Ex. Ni-Iron alloys.
Negative magnetostriction → material expand with decrease in the strength of applied magnetic field and its contracts with increase in the strength.

\( y = \frac{\text{stress}}{\text{strain}} \)

\( \text{Mater} \)

\( \text{y} \)

\( \text{Expands} \)

\( \text{Contracts} \)

\( \text{Ni} \)

\( \text{Fe} \)

\( \text{Co} \)

Application of magnetostriction →

Under water sound detection

Generation of supersonic sound

Generation of high freq. oscillation.

Villari Effect →

It is converse of magnetostriction

The longitudinal deformation leads to change in magnetic permeability of material in the direction of applied stress.
Case-1 Material with (+ve) Y (Young modulus) (Strain)

→ μ ↑ with expansion.

→ μ ↓ " contraction.

Ex- Ni-Fe alloys

Case-2 Material with (-ve) Y strain

→ μ ↑ with contraction

→ μ ↓ " expansion.

Ferro magnetic domain → (Conventional).

(a) $H=0$

(Net domain state)

(b) $H>0$

(Growth of domain)

(c) $H>0$

(Net magnetization is zero)

(d) $H>0$

(Single domain formation)

(e) $H>0$ - Rotation of domain in the direction of field
In ferromagnetic material (Indemagnetize state) few several domain are present and each domain is spontaneously magnetize (having their own saturation magnetization), but the direction of magnetization of the various domain are such that as a whole specimen there is zero magnetization as shown in Fig. (a).

When a mag. field is imposed on the material domains are lined up with the field growth at the expense of unaligned domain. (Conversion from...
multi-domain state to single domain) as shown in fig. (b) & (c).

This process continues until the most favorably domain remains in material as shown in fig (d) when domain growth completed. A further increase in mag. field causes domain to rotate and aligned parallel to mag. field as shown in fig (e).

At this instant material reaches saturation magnetization and no further increase will take place on increasing the strength of mag. field.

Que:- During the process of magnetization of ferromagnetic material, the magnetic domain
(a) Only expand
(b) Neither rotate nor expand
(c) Rotate first and then expand
(d) Expand first and then rotate

Que:- Paramagnetic susceptibility of material
(a) Increase linearly with temp
(b) Decrease
(c) Increase " \frac{1}{T} \longrightarrow \chi_m = \frac{C}{T} 
(d) Decrease \frac{1}{T}
Ex: \[ \frac{D}{d} \] atom orbital diameter to 3-d orbital diameter

It is a function of the ratio of atomic diameter.

Exchange interaction energy is due to creation of dipoles of iron, Co, Ni. Is known as exchange interaction energy.

Exchange interaction energy is a function of magnetic property of individual domains. Domains are aligned parallel or perpendicular to one another.

Permanent magnetism of atomic moment in individual domains are aligned parallel to one another.

Dc: Which of the following are properties of magnetic material?

(a) Remanent magnetism
(b) Ferragomagnetic
(c) Dimagnetism
(d) Ferromagnetic

To which of the following materials, do the very low temp diamagnetic materials convert?

- Dimagnetic material
- Ferromagnetic material
- Ferragomagnetic material
- Remanent magnetism

Consider the following statement about dia magnetism.
For parallel alignment, the ratio must be in the range of $(1.4 - 2.7)$.

\[ \text{Lies below} \]

Comparison between magnetic materials:

<table>
<thead>
<tr>
<th>Materials</th>
<th>$X_m$</th>
<th>'$X_m'$ vs '$T$'</th>
<th>Alignment of dipoles</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamagnetic</td>
<td>Small &amp; -ve</td>
<td>$X_m$ is independent of temp.</td>
<td>no dipoles.</td>
<td>Si, Ge, Cu, Au, diamond, NOCl</td>
</tr>
<tr>
<td>Paramagnetic</td>
<td>(+ve) &amp; small ($\approx 10^{-3}$)</td>
<td>$X_m = \frac{C}{T}$ Curie law \cite{1}</td>
<td>random</td>
<td>MnSO$_4$, NiSO$_4$, FeSO$_4$, Fe$_3$O$_4$</td>
</tr>
<tr>
<td>Ferromagnetic</td>
<td>(+ve) &amp; very large</td>
<td>$X_m = \frac{C}{T-\Theta_1}$ Curie-Weiss law \cite{2}</td>
<td>$X_m \rightarrow \infty$</td>
<td>Fe, Co, Ni</td>
</tr>
<tr>
<td>Anti-Ferromagnetic</td>
<td>(+ve) &amp; small</td>
<td>$X_m \rightarrow X_m^{\infty}$</td>
<td>$\uparrow \uparrow \uparrow \uparrow$</td>
<td>MnO, MnO$_2$, FeO</td>
</tr>
<tr>
<td>Ferrimagnetic</td>
<td>(+ve) &amp; large</td>
<td>$X_m \rightarrow \infty$</td>
<td>$\uparrow \uparrow \uparrow \uparrow \downarrow$</td>
<td>Ferrites, Garnet</td>
</tr>
</tbody>
</table>
Core losses →

1. Eddy Current Losses
2. Hysteresis losses

\(\text{Eddy Current Losses} \rightarrow \text{Eddy Current refers to a circulating current which are introduce in a seath of a conducting material when it subject to an a.c field.}\)

Eddy current losses are given by:

\[
\text{(Watt/m}^3\text{)} \quad P_{\text{eddy}} = \frac{\pi B^2 F^2 t^2}{P \cdot B}
\]

where:
- \(B\) - mag. flux density
- \(F\) - freq. of applied ac field
- \(t\) - thickness
- \(P\) - resistivity
- \(B\) - constant

\[\text{f} \uparrow \rightarrow \text{P}_{\text{eddy}} \uparrow\]

\[\text{f} \uparrow \rightarrow \text{P}_{\text{eddy}} \uparrow\]

Eddies are \(\text{h}\)

To reduce eddy current losses are higher freq.

Iron cores are laminated or 8i-steel is used.

(higher d.c resistivity.)
Si-Steel → is a ferrite.

(2) **Hysteresis losses**:

\[ P_{hy} \, (\text{Watt/m}^3) = \eta B^n f \]

where - 
- \( B \) - mag. flux density
- \( f \) - freq. of ac field
- \( \eta \) - material Constant
- \( n \) - an exponent

\[ P_{hy} \propto \text{Area of hysteresis loop} \]

→ Soft mag. material and soft ferrites has low coercive force and "less area of hysteresis loop" so they are used in high freq. electromagnetic devices.

\[ \text{Redendivity} \rightarrow \text{Residual flux density is called redendivity} \]
Coercivity \[\rightarrow\] max\{m\} value which a coercive field can attain.

\[\text{Soft} + \text{hard magnetic material} \rightarrow \text{Soft magnetic material} \rightarrow\]

\[\Rightarrow \text{These materials are easy to magnetise} \& \text{demagnetise}\]

\[\Rightarrow \text{These materials favour rapid switching of magnetization}\]

\[\Rightarrow \text{it means high freq}\]

\[\Rightarrow \text{to applied ac field}\]

\[\Rightarrow \text{These materials have low retentivity}\]

\[\Rightarrow \text{Low = coercivity}\]

\[\Rightarrow \text{High permeability}\]

\[\Rightarrow \text{High magnetic saturation}\]

\[\Rightarrow \text{Low hysteresis losses} \text{ (because of lesser area of hysteresis loop)}\]

\[\Rightarrow \text{These materials are used for transformers \& inductive core, to minimize energy dissipation (reduction in hysteresis)}\]
→ desirable for electromagnets

Ex: (a) Si-steel / Soft iron / Fe-Si alloy: it is used upto power freq. (50 to 60 Hz)

→ It is used in power transformer.

→ When 5% Si is added it increases max. permeability d.c. resistivity and reduces the area of hysteresis loop (low hysteresis losses).

→ Low eddy current losses.

11. Fe-Ni alloy:

(a) 36% Ni (Invar) → used for high freq. applications, such as used as high speed relay & transformer.

(b) 50% Ni → used for magnetic memory

(c) 77% Ni → used for precision voltage & current transformer.

(d) Permalloy → 45% Ni

(e) Super alloy → 79% Ni.

(f) Mu-metal → 75% Ni.

Alloys (a), (c) & (f) have high permeability and less area of hysteresis loop.
Hard magnetic materials → These materials are also called permanent magnet material. These materials retain their magnetisation and are difficult to demagnetize. These materials have high retentiivity, high Coercivity, high permeability, high magnetic saturation, and high Curie point or temp.

→ high hysteresis losses (because of large area of B-H curve).

Ex: Carbon steel → Used as magnet for latching relays or compass needle.

(b) Tungsten steel: → Used as magnets in d.c motors.
(3) Alnico (Al, Ni, Co) — Their magnetic properties are very stable with temp.

(4) Ba-ferrite

(5) Remalloy

(6) Cunite (Cu, Ni, Fe)

Que:— For permanent magnetic material.
(a) the area of hysteresis loop should be small.
(b) The initial relative permeability should be large.
(c) The residual induction + coercive field should large.
(d) " " " " small.

Que:— Consider the following statement:
In a T/F the core material should be low.

(a) Coercivity
(b) Retentivity
(c) Permeability

Que:— Magnetic Cores required for radio freq. application should have.

<table>
<thead>
<tr>
<th>Hysteresis</th>
<th>Eddy Current Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

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for radio freq, the freq. will be high.
we use soft material so the B-H curve will be less
so the eddy + hyst. loss will be low.
How can eddy current loss in the core of T/F
be minimize

1) by ↑ the resistivity of core
2) by using laminated sheets with insulator coating
3) by using highly insulating non-magnetic material for
   the core
4) by using the Paramagnetic material as the core

Which material is used for making permanent magnet?
(a) Si-Steel
(b) Permalloy
(c) Carbon-steel
(d) None of these

The hysteresis loop for material of the core of Transformer
should be
(a) Short + wide
(b) Short + narrow
(c) Tall + narrow
(d) Tall + wide
Match list I + list-II

**List-I** 

1. Permanent magnet
2. High freq. application in (MHz) range.
3. Electromagnets.
4. Very high freq. (GHz)

**List-II** 

Ferrites
Garnets
Hard mag. material
Soft mag.

(0) 1 2 4 3
(b) 2 1 3 4
(c) 3
(d) 1 2 3 4
Conducting + Insulating Materials.

Conductors

Ohm's Law (point form)

\[ J = \sigma E \]

Proof:

Under the influence of electric field the motion of electron in conducting material have two component

1) random motion of \( \bar{e} \) which depend on \( T \)

2) directed motion of \( \bar{e} \) applied external field

The force experienced by \( \bar{e} \) under the influence of external field is given by

\[ \frac{md^2x}{dt^2} = -eE \]

\[ \frac{d^2x}{dt^2} = -\frac{eE}{m} \]
\[ \frac{dx}{dt} = -\frac{ee}{m} t + V_{\text{random}}. \]

\[ \text{drift velocity of } \bar{e} \text{ is defined for avg collision time which is the avg. time b/w the two successive collision of } \bar{e}. \]

\[ \text{Over the avg. collision time random velocity of } \bar{e} \text{ is 0.} \]

\[ V_d = -\frac{ee}{m} t + 0 \]

Where \( t \) = avg. collision time

\[ t \propto \frac{1}{\lambda^2} \]

Now,

\[ V_d = -\frac{ee}{m} t \]

\[ V_d = \frac{ee}{m} t \]

\[ V_d = \frac{ee}{m} \]

\[ \mu = \frac{ee}{m} \]

\[ J \text{- Current density} \]

\[ = \frac{p \cdot V_d}{t} \]

\[ = n_0 e \cdot V_d \]

\[ = n_0 e \cdot \frac{ee}{m} \]

\[ J = \frac{n_0 e^2}{m} \cdot t \cdot E \]

\[ J = \sigma E \]

\[ \sigma \text{- Conductivity} \]

\[ \sigma = \frac{n_0 e^2}{m} \cdot t \]
Effect of Temp. on Conductivity

Conductor: \( \sigma = \frac{ne^2T}{m} \)

\[ \downarrow \sigma \propto \frac{n}{\sqrt{T}} \uparrow \]

With increase in temp, there is no appreciable increase in \( n \) as conductor have already large no of \( \bar{e} \) in their conduction band. So overall conductivity decreases with increase temp.

Semi Conductor:

\[ \sigma \propto \frac{n}{\sqrt{T}} \]

\[ n_i^2 = A_0 T^3 \beta \frac{e^{E_g_0/kT}}{e^{E_g/kT}} \]

\[ n_i = n = A_0 T^{3/2} e^{-E_g_0/2kT} \]

\[ \frac{n}{\sqrt{T}} = A_0^{1/2} T e^{-E_g_0/2kT} \]

Since \( \sigma \propto \frac{n}{\sqrt{T}} \)

\[ \sigma \propto T e^{-E_g_0/2kT} \]

\[ \uparrow \sigma \propto \frac{T}{e^{E_g_0/2kT}} \]

Mean free path (\( \lambda \)): It is define as the avg. distance travelled by \( \bar{e} \) before collision takes place.
Relaxation time: It is defined as the time required at which the drift velocity of e reduces 37% of its value after the removal of electric field.

For isotropic material, the relaxation time and the Aug collision time are equal.

\[ t = \frac{1}{\nu_d} \]

Factors affecting resistivity of metals

1. Temperature

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

\[ T \uparrow \rightarrow \rho \uparrow \]

Where \( \alpha \) - Temp. coefficient of resistivity

\[ \alpha = +ve \ (\text{for metal}) \]
1. **Alloying** → If an alloy is found by mixing two metals, then the total resistivity will be greater than individual resistivity of metal.

   \[
   \rho_{\text{Alloy}} = \rho_{\text{Thermal}} + \rho_{\text{Residual}}
   \]

   → Metallurgical's Rule

   Where
   \[
   \rho_{\text{Thermal}} - \text{thermal comp. of resistivity}
   \]
   \[
   \rho_{\text{Residual}} - \text{Residual}
   \]

2. **Resistivity** has two components:

   → **Thermal Resistivity** → This component arises due to lattice vibration in material which increases with Temp.

   * This can be decrease to zero, by reducing the temp \( T_2 \) to zero (0°K).

   **Residual** → This comp. Arises due to impurity and defect present in the material.

   * This is independent of Temp.

   * Resistivity above temp. known as Debye temp., increases linearly with increasing Temp.
Super Conductors →

Super Conductivity → A state of material in which it has zero resistivity is called super conductivity.

Transition Temp \( (T_c) \) → The critical temp at which there is change of state from normal to super conducting and reverse is known as transition temp.

R. vs Temp →

\[
\begin{array}{c}
\text{Resistance} \ R \uparrow \\
\text{Super Conducting State} \leftarrow \text{Normal State} \\
\text{Tc} \rightarrow
\end{array}
\]

Super Conductor → The material whose resistivity become very small or zero after the critical temp of transition temp are known as super conductor.

Empirical Criteria → Materials having no. of valance \( \pm \) electron \( (z) \) from 2 to 8 generally show super conductivity.
Thermo electric Effect →

→ Seeback effect

→ Peltier effect

Seeback Effect → When two dissimilar atom are joint at their end and junction and are maintained at different temp. then on temp exist across the junction.


Peltier Effect → An electric current which flows through a rod consisting of two dissimilar metal causes a decrease in temp. at one end and increase in temp. at the other end.

It is converse of Seeback effect
Condition for super Conductivity →

Resistivity should be zero

\( \mu_T = 0 \) (perfect diamagnetism).

Critical field \( (H_c) \): — It is the minimum field required at a given temp to destroy super conductivity. Its value is given by —

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

Where

\( H_0 \) — Critical field at 0°K

\( H_c \) — Critical field at \( T \)

\( T_c \) — Transition or critical temp.

→ Transition from the superconducting state to normal state & vice-versa is reversible.

→ Transition temp can be reduce by the application of mag. field.
Transition Temp $\rightarrow$

* Transition temp shows $\max$ value for $x = 3, 5, 7$

**Meissner’s Effect** $\rightarrow$ The repulsion of magnetic flux from the interior of a piece of superconducting material, as the material undergoes to the transition to the superconducting phase, is known as Meissner’s effect.

In superconductor

\[ B = 0 \]

\[ \mu_0 (H + M) = 0 \]

\[ M = -H \]

\[ = \chi_m H \]

\[ \Rightarrow \chi_m = -1 \]

\[ \chi_m = \mu I - 1 = -1 \]

\[ \mu I = 0 \]

perfect diamagnetism.
Que: The critical field for Niobium is $1\times10^5$ A/m at 8K and $3\times10^5$ A/m at 0K. Calculate critical temp of material.

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

$$10^5 = 3\times10^5 \left[ 1 - \left( \frac{\Theta}{T_c} \right)^2 \right]$$

$$\frac{1}{2} = 1 - \left( \frac{\Theta}{T_c} \right)^2$$

$$\frac{64}{T_c^2} = \frac{1}{2}$$

$$T_c = 128$$

$$T_c = 113.31 \text{ K}$$

Silsbee Rule \( \rightarrow \) If a super conducting material causes a current such that magnetic field which it produced is equal to critical field, the super conductivity disappears.

\( \rightarrow \) The current density at which the super conductivity disappears is known as critical current density.

Let us consider a long wire of super conducting material of radius \( R \) having a centre current \( i \) then according to Ampere's Law.

$$\oint H \cdot dl = i$$

$$H \cdot 2\pi R = i \quad \cdots \cdots \text{(1)}$$

$$H = \frac{i}{2\pi R}$$
Critical Field

Critical Current density $\rightarrow (J_c)$

$$J_c = \frac{jc}{\pi}$$

$$J_c = \frac{Hc \times A}{\pi R^2}$$

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

- This rule prevents the use of super conductor as coils for the production of strong mag. field.

- The field require to destroy the super conductivity need not be an external field it may be internal as well.

Types of super conductor:

- Type-1
- Type-2

Type-1 Super Conductor --- They are also called soft super cond.
Their critical field and transition temp are low.

They exhibit complete Meissner's and Silsbee rule.

The change of state from normal to superconducting and vice versa is abrupt.

\[ M \]

\[ H \]

Normal State

Super Conducting State

Ex: Zn, Pb, Hg, Al, In etc.

Type-2 Superconductor: They are also called hard superconductor.

01 non-ideal superconductor.
They exhibit incomplete Meissner's effect & Silsbee rule.

The critical field & transition temp are high. The change of state from normal to super cond. & vice versa is gradual. These super conductor exhibit incomplete Meissner's effect in vortex region. (-Nb₃Al, NbTi etc.)
Application:

- Magnets for nuclear fusion.
- Magnetic resonance Imaging (MRI)
- Generators & Motors
- Switching elements like "Cryotrons"

Factors affecting superconductivity & transition temp:

1. Frequency \( \rightarrow \) S. Cond. decrease with increase freq. It is observed upto radio freq. (above 10 MHz)
   
   Above 10 MHz resistivity increases at infrared freq. \((10^{13} \text{Hz})\) the resistivity is same as normal state

2. Entropy \( \rightarrow \) Entropy increase on going from S. Cond state to normal state. It means S. Cond. have low entropy

3. Thermal Conductivity \( \rightarrow \) It decreases on going from super conducting state to normal state

4. Isotope Mass \((M)\) \( \rightarrow \)

   \[ T_c \propto \frac{1}{\sqrt{M}} \]

   Eq: Mg (Mercury)
M → 19.95 - 203.4° AMU
Tc → 4.185 K - 4.16 K
≈ 4.1 K

1) Mechanical stress or Pressure — Transition temp of S. Cond material

James with applied mech stress or Pressure
of Ex. then are some metal Cs (Cesium).
that become S. Cond only if large pressure is applied to them.

Low resistivity Conducting material → Silver has
Low resistivity
than Cu, but it is very costly, which restrict
its use for commercial purpose.
Al is cheaper than Cu, so it is often used
as a Cu substitute in electrical Power system.

Brass — Alloy of Zn-Cu

Properties of brass — high tensile strength but lower conductivity than Cu.
Good corrosion resistant
Used in reostate, lamp holder and plug point
Bronze → Alloy of Cu, Tin, Al, Ni & Si.

Superior mechanical property and corrosion resistance than brass.

Phosphor bronze — Used in current carrying spring and brush holders.

Silicon bronze — Wires & telephone ports.

Solders

Solder is an alloy which is used to joint two or more pieces of metal.

The melting point of solder lower than the material to be joined.

Types

1. Soft Solder → (T < 400°C)
   Alloy of Tin & lead.

2. Hard Solder → (T > 400°C)
   Alloy of Cu-Zn
   → Brazing Solder
   → Silver
High resistivity Conducting materials:

Comparison between high resistivity conducting materials:

<table>
<thead>
<tr>
<th>Material</th>
<th>Composition</th>
<th>$\rho$ at 20°C ((\Omega\cdot m))</th>
<th>Operating Temp</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nichrome</td>
<td>Ni + Cr + Mn + Fe</td>
<td>$100\times 10^{-8}$</td>
<td>Upto 1100°C</td>
<td>Heating, element in soldering, iron furnaces</td>
</tr>
<tr>
<td>Constantan</td>
<td>Cu + Ni</td>
<td>$52\times 10^{-8}$</td>
<td>Upto 500°C</td>
<td>Wire wound resistors, Reo crystal strain gauge</td>
</tr>
<tr>
<td>Manganin</td>
<td>Mn + Ni + Cu</td>
<td>$48\times 10^{-8}$</td>
<td>~ 60°C</td>
<td>Precision instruments, bridge potentiometer</td>
</tr>
<tr>
<td>Tungsten</td>
<td>metal</td>
<td>$5.51\times 10^{-8}$</td>
<td>Upto 3300°C</td>
<td>Heating filaments such as bulbs, CRTs</td>
</tr>
</tbody>
</table>

Carbon $\rightarrow$
Natural source of C is diamond & Graphite

Pure carbon is a semiconductor with negative temp coefficient of resistivity, brushes for electrical m/c)
Non wire resistor

Lead (Pb) – High anti corrosion properties because of this properties it is used for laying of underground and under water cable for power and communication lines.
Platinum → Used for contact fabrication in low Power rating contactors

Ni: Used for making electrode

**INSULATING MATERIALS**

Ceramics:

- Properties: 1. These materials are hard, strong, dense and brittle
  2. High temp. Stability
  3. Generally inorganic material (absent of C so it is called inorganic) Except Sic
  4. Generally Crystalline. (Except Amorphous Glass)
  5. These materials are non metallic Oxide, Nitrides and Carbides.
  - Ex: Garnet, BaTiO₃, Ferrites, TiO₂ (Rutile), Ti dioxide, Quartz, ZnS, MgO, SiC, Cds etc.

Types of Ceramics →

1. Porcelain ($E_r < 12$)
2. Steatite ($E_r < 12$)
3. Alumina ($E_r < 12$)
4. Titonate ($E_r > 12$)
Porcelain - Used in low and high voltage applications.
   - Used in insulation or transmission and distribution of P.S.

Steatite - Used in high freq. application.

Alumina - High temp. application,
   - Used in C.B. and resistance cores.

Titania - Used in capacitor application, due to high dielectric constant.

Another classification of Ceramic →

\[ \varepsilon_r < 12 \] used as insulator
   - Ex. Alumina, Porcelain, steatite

\[ \varepsilon_r > 12 \] - Used in capacitor application because of high dielectric constant
   - Ex. Titania + Ruhile.

2) Transformer Oil → Transformer cores are dipped in mineral oil
   - Known as T/F Oil
   - It acts as an insulator.
It act as on cooling medium
Parameter determining the properties of T/F oil

Viscosity — (It should be low)
Specific Gravity

Flash Point —

Breakdown Voltage of T/F oil decreases with contamination. Ex. moisture

To absorb moisture, absorbents added are Silica gel and Allumina.

(3) Askarels

They are fire resistance insulating material

Two types of Askarels.

Chlorinated benzene

Biphenyl

Now a days they are not used in T/F and Capacitor because on decomposition they produce Toxic + poisonous Gases.
Semiconductor Materials

→ ESM (Elemental S/c materials)
→ CSM (Compounded S/c materials).

- As conductivity and band gap are limited for ESM, hence their usefulness is limited. So Group-3
- So, Gp. III-IV, II-III, IV-VA, III-VA. S/c is used to provide better properties.

ESM — E — Ge, Si, C, B, Al, Ga, P, As, Sb, Bi etc.

Es → It is pentavalent S/c material
Used as donor N-type S/c material.
When it is alloyed with Gallium, then it is used in fabrication of LED.

Se → (Selenium) → It is used in photo voltaic cell.

CSM →

III-V S/c material — They provide wider range of band gap and extended mp range of device.
→ Structure is Zinc blende & diamond cubic.
Ex - GaAs, AlP etc

GaAs:
1. Large band gap material
2. Large electron mobility which helps in high speed switching
3. Direct band gap material
4. It is 10 times costlier than Si
5. It is 3.5 times faster than Si based device

In GaAs crystal, Ga substitute corner and face atoms whereas As takes place of 4 inside atoms.

Application:
1. LED
2. LASER
3. Satellite amplifier
4. Group - II-III S/c material
   - Ex: CdS, CdSe, CdTe, ZnS, ZnSe etc
     - Used in photo conductor

   Bond Gap is larger than Group III-II S/c
   → CdS, CdSe, CdTe can be used as photo conductors
\[ \frac{IV - IV}{Ex - SiC} \]

Dr. Bond gap is 3 eV

\( X - SiC \) can be used for high Temp. devices.

**Drawback**: Expensive, if not easy to manufacture.

\[ \frac{IV - VII}{S/C} \]

\textit{Ex}: PbS, PbSe, PbTe

In these \( S/C \) excess \( Pb \) gives rise to \( n \)-type \( S/C \)

and less \( Pb \) gives rise to \( p \)-type \( S/C \).

\( \Rightarrow \) Amorphous \( S/C \) material →

Structure is similar to supercooled liquid

\( \Rightarrow \) Atom upto first nearest neighbours are arranged periodically,

but the atoms which are away from the first nearest neighbour are found to be arranged randomly.

There are 3 types of amorphous \( S/C \)

\( \Rightarrow \) Elemental amorphous \( S/C \)

Ge, Si, Se, Te

\( \Rightarrow \) Covalent \( S/C \)

Ge, Te

\( \Rightarrow \) Ionic

\( Al_2O_3, V_2O_5 \)
Hall Effect

When a current carrying specimen is placed in a transverse mag. field then an electric field induced \( \mathbf{E} \) to current \( \mathbf{I} \) mag. field.

Let us consider a current carrying specimen \( \mathbf{I} \) is placed in mag. field \( \mathbf{B} \).

Assume N-type

\[ \text{S/c} \]

Let us consider an N-type S/c. Suppose an electric current flow in positive Y direction and mag. field is applied \((-x)\) direction. A force called Lorentz force is excited on \( \mathbf{e} \) as well as holes in \((+ve)\) Z direction.

The minorities hole will recombine with majority electron. The movement of \( \mathbf{e} \) in the upwards direction disturbs the local neutrality of the S/c.
The application of Lorentz force will result in the formation of a negative layer on the upper side of specimen and positive layer due to immobile ion on the bottom side of specimen at equilibrium.

\[ \varepsilon E_H = \varepsilon \nabla \times B \]

\[ \frac{V_H}{d} = \nabla \cdot B \]

\[ V_H = \nabla \cdot d \cdot B \]

\[ J = \frac{\hat{A}}{A} \]

\[ \tau = \frac{\hat{A}}{A} \]

\[ \tau = \frac{\hat{A}}{A} \]

\[ \rightarrow \]

\[ V_d = \frac{J}{P} = \frac{i}{A \cdot P} \]

From (1)

\[ V_H = \frac{1}{AP} \cdot B \cdot d \]

\[ = \frac{1}{(d \omega) P} \cdot B \cdot d \]

\[ V_H = \frac{Bi}{P \omega} \]

\[ V_H = R_H \left( \frac{Bi}{\omega} \right) \]

Where \( R_H \) - Hall coefficient

\[ R_H = \left\{ \begin{array}{ll} \frac{1}{P} & \text{when} \ \varepsilon \ \text{is moving drift velocity} \\
\frac{3\pi}{8P} & \text{when} \ \varepsilon \ \text{is motion is random.} \end{array} \right. \]
\[ R_H = \begin{cases} 
-\text{ve} & \text{n-type} \\
+\text{ve} & \text{p-type} 
\end{cases} \]

\[ U_H = \begin{cases} 
-\text{ve} & \text{n-type} \\
+\text{ve} & \text{p-type} 
\end{cases} \]

For comparable \( \varepsilon \) & \( \text{hole} \) concentration,

\[ R_H = \frac{1}{p} \cdot \frac{p \mu_p^2 - n \mu_n^2}{(p \mu_p + n \mu_n)^2} \]

For intrinsic \( s/c \) -

\[ n = p = n_i \]

\[ R_H = \frac{1}{niq} \cdot \frac{n_i [p \mu_p^2 - n \mu_n^2]}{n_i^2 [p \mu_p + n \mu_n]^2} \]

\[ R_H = \frac{1}{ni^2q} \left( \frac{p \mu_p - n \mu_n}{p \mu_p + n \mu_n} \right) \]

Since \( \mu_n > \mu_p \)

\[ R_H = -\text{ve for intrinsic s/c} \]

\[ R_H = \begin{cases} 
\text{Si} & \rightarrow -10^9 \\
\text{Ge} & \rightarrow -10^6 
\end{cases} \]
Application -

1. To determine the type of semiconductor
2. To determine carrier concentration
3. To calculate mobility of carriers
4. It is used in hall effect multiplexer
5. Can be used as a magnetic field meter

**Electret** → dielectric materials having permanent electrical dipole moment are known as electret.

**Gauss Meter** → It is used to measure flux density.

It is based on hall effect material.