Content:

Introduction, Electrical Polarization Mechanisms, Internal fields in solids (qualitative), Clausius-Mossotti relation (Derivation) and its implications, Properties and Frequency dependence of Dielectric constant, Dielectric loss, Solid, Liquid and Gaseous dielectrics. Application of dielectrics in Capacitors, Transformers (Oils), SF6 in High Voltage application, Numerical Problems.

Introduction:

Materials such as glass, ceramics, polymers, and paper are classified as *non-conductors* because they inhibit the flow of electric current. These materials are widely used for insulation purposes. When their primary function is to prevent electrical conduction, they are referred to as insulators.

However, when placed in an electric field, these materials undergo internal rearrangements that allow them to store electric charge. In such cases, they are termed dielectrics. For a material to function effectively as a dielectric, it must first be an insulator. Thus, every dielectric is an insulator, although not all insulators are used as dielectrics.

The resistivity of an ideal dielectric is infinity, in practice dielectrics conduct electric current to a negligible extent and their resistivities range from 10^{10} to $10^{20}\Omega$m.
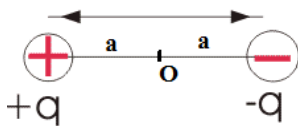
Electric dipole and dipole moment

Figure 1: Electric dipole

A pair of equal and opposite charges separated by a distance is called an **electric dipole** and the product of the magnitude of one of the charges and the distance of their separation is called **dipole moment**.The dipole moment for this arrangement is given by

$$\mu = (2a)\, q \ldots\ldots\ldots (1)$$

Induced dipole and Permanent dipole

If an atom is placed in an electric field of strength 'E', the electron cloud will be displaced in the direction opposite to 'E' by a distance 'd' with respect to the nucleus. The centers of gravity of positive and negative charges in the atom no longer coincide.

The atom is equivalent to the system of charges, q=Ze of equal magnitude but opposite in sign separated by a distance 'd'. Such a system is called an **electric** dipole.
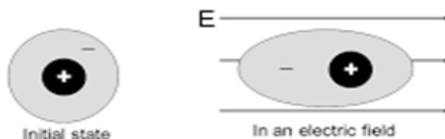

Figure 2

The dipole is **induced** in the atom due to the action of external electric field. Though a dipole as a whole is electrically neutral, the induced dipole sets up its own electric field which is opposite in direction to the external field.

The dipole moment μ is a vector, directed along the axis of the dipole from the negative charge to the positive charge.

The induced dipole moment is proportional to the field strength. The larger the field, greater the displacement of charges and

hence larger the induced dipole moment. The induced dipole moment is given by

$$\mu = \alpha E$$

α is the **polarizability** of the molecule. The unit of polarizability is Fm^2. The induced dipole moment vanishes as soon as the electric field is switched off.

Permanent dipole:

In some molecules known as polar molecules, the centers of gravity of the charges of opposite sign are separated even in the absence of external field. Such molecules are said to have intrinsic dipole moment and carry permanent dipoles.

Polar and non-polar dielectrics:

A dielectric material doesn't possess any free electrons. All the electrons are bound very strongly to the respective nuclei of the parent molecules. Each molecule consists of equal amount of positive and negative charges. All the positive charges are concentrated in the nuclei, which are surrounded by electron clouds in which all the negative charges are distributed.

In the molecules of some dielectric materials, the effective centre of the negative charge distribution coincides with the effective centre of the positive charges. Such materials are called non-polar dielectrics.eg Hydrogen, carbon dioxide etc.

In some dielectric materials, the effective centres of the negative and positive charges in the molecules do not coincide with each other even in the absence of any external field. Each molecule behaves as though it consists of a pair of equal negative and positive charges separated by a small distance. Such a pair is referred to as a permanent dipole and the materials comprising of such dipoles are called polar dielectrics. HCl, H_2O etc.

Polarization

Consider an electrically neutral slab inserted between the plates of a parallel plate capacitor as shown in figure 3.
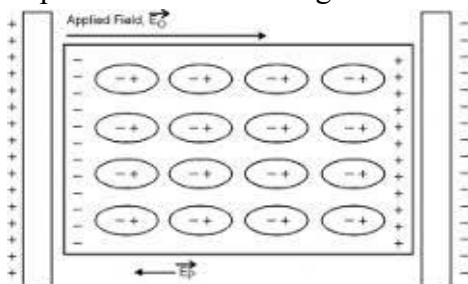

Figure 3

Dielectric is imagined to be divided into large number of identical cells of volume dv. Under the action of external electric field, charges are induced in each cell and each cell acquires a dipole moment dµ.

Then intensity of polarization "P" is defined as the total dipole moment per unit volume of the material.

$$P = \sum \frac{d\mu}{dv} = \frac{\mu}{v}$$

Dielectric susceptibility

The magnitude of polarization is directly proportional to the intensity of the electric field.

Thus,   P=χ ε₀E (for linear dielectrics)

χ is the proportionality constant and is called the dielectric susceptibility of the material. It characterizes the ease with which the dielectric material can be influenced by an external field. P is a measure of the polarization produced in the material per unit electric field.

Relation between ε_r and χ

In order to describe the combined effects of the applied electric field **E** and electric polarization **P,** an auxiliary vector **D** called **Electric displacement vector** is introduced.

$$D= \varepsilon_0E+P$$

Substituting for $P=\chi\,\varepsilon_0E$ in the above equation

$$D= \varepsilon_0E+ \chi\,\varepsilon_0E= (1+ \chi)\,\varepsilon_0E= \varepsilon_0\,\varepsilon_rE= \varepsilon E \qquad \text{where } \varepsilon_r = 1+\chi$$

ε_0 and ε are the permittivity of the free space and the dielectric material respectively. ε_r is the relative permittivity or the dielectric constant.

Types of Polarization
i) Electronic or Atomic Polarization:
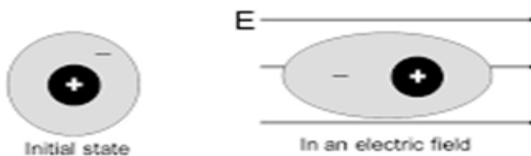

Initial state   In an electric field

Figure 4: Electronic Polarization

This is the polarization that results from the displacement of electron clouds of atoms or molecules with respect to the heavy fixed nuclei to a distance that is less than the dimensions of atoms or molecules (figure 4). This polarization sets in over a very short period, of the order of 10^{-14}-10^{-15}s. It is independent of temperature.

The polarization is given by $P_e=N\alpha_eE$ …..(1)
Where N is the number of atoms/unit volume, α_e is electronic polarizability.
We have $P=\chi\varepsilon_0E$ or $\chi = \dfrac{P}{\varepsilon_0E}$……(2)

Dielectric constant $\varepsilon_r = 1 + \chi$ ….(3)

Substituting eqn. (2) in eqn. (3)
$$\varepsilon_r = 1 + \frac{P_e}{\varepsilon_0 E} \quad .....(4)$$
Substituting for P_e from eqn (1) in eqn (4)
$$\varepsilon_r = 1 + \frac{N\alpha_e E}{\varepsilon_0 E}$$
$$\varepsilon_r = 1 + \frac{N\alpha_e}{\varepsilon_0} \quad .... \text{ (5) or } \quad \alpha_e = \frac{\varepsilon_0(\varepsilon_r - 1)}{N}$$

ε_r is the dielectric constant of a non-polar gaseous dielectric. The above equation indicates that the dielectric constant depends on the polarizability of a molecule and the number of molecules in a unit volume of the dielectric.

ii) <u>Ionic Polarization:</u>

Ionic polarization occurs in ionic crystals. It is brought about by the elastic displacement of positive and negative ions from their equilibrium position. Eg: Sodium chloride crystal.

A NaCl molecule consists of Na^+ ion bound to Cl^- ion through ionic bond. If the interatomic distance is 'd', the molecule exhibits an intrinsic dipole moment equal to "qd" where q is the charge of the electron and d is the distance of separation.
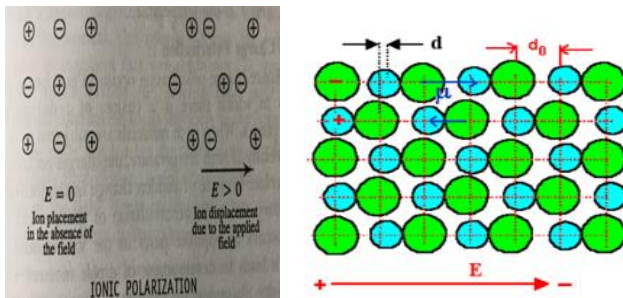

Figure 5: Ionic Polarization

When ionic solids are subjected to an external electric field, the adjacent ions of opposite sign undergo displacement (figure 5). The displacement causes an increase or decrease in the distance of separation between the atoms depending upon the location of the ion pair in the lattice. This polarization takes 10^{-11}-10^{-14}s to build up and is independent of temperature.

Ionic polarization is given by $P_i = N\alpha_i E$

For most materials, the ionic polarizability is less than electronic polarizability. Typically, $\alpha_i = \frac{1}{10}\alpha_e$

iii) Orientation or dipole Polarisation
This polarization is a characteristic of polar dielectrics which consists of molecules having permanent dipole moment. In the absence of external electric field, the orientation of dipoles is random resulting in a complete cancellation of each other's effect (figure 6).

When the electric field is applied, the molecular dipoles rotate about their axis of symmetry and tend to align with the applied field and the dielectric acquires a net dipole moment and it is orientation polarization.
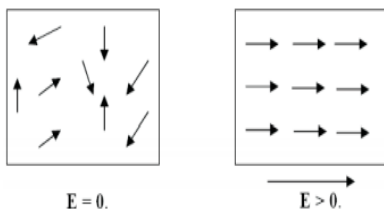

$E = 0.$ $E > 0.$

Figure 6: Orientation Polarization

The dipole alignment is counteracted by thermal agitation. Higher the temperature, the greater is the thermal agitation. Hence, orientation polarization is strongly temperature dependent.

In case of solids, the rotation of polar molecules may be highly restricted by the lattice forces, leading to a great reduction in their contribution to orientation polarization. Because of this reason, while the dielectric constant of water is about 80, that for solid ice is only 10.

As the process of orientation polarization involves rotation of molecules, it takes relatively longer time than other two polarisations. The build-up time is of the order of 10^{-10}s or more.

The orientation polarizability $\alpha_0 = \dfrac{\mu^2}{3kT}$ and orientation polarization $P_0 = \dfrac{N\mu^2 E}{3kT}$

Orientation polarization is inversely proportional to temperature and proportional to the square of the permanent dipole moment.

4. Space charge or Interface polarization:

This polarisation occurs in multiphase dielectric materials in which there is a change of resistivity between different phases, when such materials are subjected to an electric field, especially at high temperatures, the charges get accumulated at the interface, because of sudden change in conductivity across the boundary (figure 7). Since the accumulation of charges with opposite faces occurs at opposite parts in the low resistivity phase, in effect it leads to the development of dipole moment within the low resistivity phase domain. E.g. Non-homogenous materials such as composites.
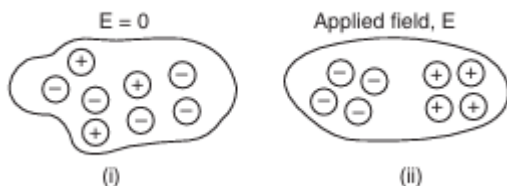
E = 0   Applied field, E

(i)   (ii)

Figure 7: Space charge polarization

Internal field in a solid for one dimensional infinite array of dipoles

When a dielectric material, either solid or liquid is subjected to an external electric field, each of the atoms develops a dipole moment and acts as an electric dipole. Hence the resultant field at any given atom will be the sum of applied electric field and the electric field due to the surrounding dipoles. The resultant local field is called the internal field (E_i)and is defined as the electric field that acts at a site of any given atom of a solid or liquid dielectric subjected to an external electric field and is the resultant of the applied field (E) and the field due to all the surrounding dipoles (E') .
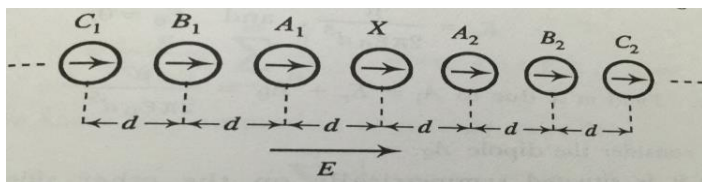
$$E_i=E+E'$$

Figure 8: Linear array of atoms in an electric field

The total field at 'X' which is the internal field E_i, is the sum of the applied field (E) and the field due to all the dipoles (E')

$$E_i=E+E' =E+\frac{1.2\mu}{\pi\varepsilon_0 d^3}$$

Thus, the combined effect of induced dipoles of neighbouring atoms is to produce a net field at the location of a given atom, which is larger than the applied field.

Clausius-Mosotti Equation:

Let us consider a solid dielectric, which exhibits electronic polarizability. If α_e is the electronic polarizability per atom, it is related to the bulk polarization P through the relation.

$$P=\alpha_e NE_i$$

Therefore $\alpha_e=\dfrac{P}{NE_i}$ ....(1)

Where N is the number of atoms per m^3 and E_i is the local field.

From Lorentz field equation $E_i = E + \dfrac{P}{3\varepsilon_0}$ …. (2)

Substituting equation (2) in equation (1) we get

$$\alpha_e = \frac{P}{N[E + \frac{P}{3\varepsilon_0}]} \qquad \text{We have} \quad E = \frac{P}{\varepsilon_0(\varepsilon_r - 1)}$$

Substituting for E in the above equation, we obtain

$$\alpha_e = \frac{P}{N\left[\frac{P}{\varepsilon_0(\varepsilon_r-1)} + \frac{P}{3\varepsilon_0}\right]}$$

$$\frac{N\alpha_e}{\varepsilon_0} = \frac{1}{\left[\frac{1}{\varepsilon_r-1}+\frac{1}{3}\right]} = \frac{1}{\left[\frac{\varepsilon_r+2}{3(\varepsilon_r-1)}\right]}$$

$$\frac{3(\varepsilon_r - 1)}{(\varepsilon_r + 2)} = \frac{N\alpha_e}{\varepsilon_0}$$

$$\frac{(\varepsilon_r - 1)}{(\varepsilon_r + 2)} = \frac{N\alpha_e}{3\varepsilon_0}$$

The above equation is known as Clausius Mosotti equation.

Solid, Liquid and Gaseous Dielectrics

Dielectric materials, which serve as electrical insulators and energy storage mediums, are broadly categorized into solids, liquids, and gases—each tailored to specific applications based on their unique physical, electrical, and thermal properties.

Solid dielectrics are the most commonly used in capacitors, high-voltage transformers, switches, overhead transmission lines, and electrical cabling. These materials typically have a moderate dielectric constant and are chosen for their durability, flexibility, moisture resistance, and thermal insulation capabilities.

Examples include inorganic substances like ceramic and glass, plastic films such as Kapton, rigid fibrous laminates, resins, varnishes, silicones, vulcanized adhesive tapes, mica, textiles like

Nomex, and rubber-like materials including PVC, MDPE, and XLPE.

Liquid dielectrics are primarily used for both insulation and cooling in transformers, reactors, capacitors, and rheostats. Their ability to suppress electrical discharges and dissipate heat makes them valuable in high-voltage applications. However, many liquid dielectrics, such as mineral oil hydrocarbons, silicone fluids, and synthetic esters, are flammable. Although alternatives like polychlorinated biphenyls (PCBs), silicone oils, and fluorocarbon oils have been explored, they tend to be toxic and expensive, limiting their practical use.

Gas dielectrics are employed in sealed electrical systems like gas-insulated transformers (GITs), gas-insulated lines (GILs), switchgears, and circuit breakers. These gases are effective at quenching electrical discharges and offer good cooling properties. Sulphur hexafluoride (SF_6) is the most widely used due to its excellent insulating performance, though its decomposition can produce highly toxic compounds such as di-sulphur decafluoride. Other gases used include nitrogen, air, carbon dioxide, and hydrogen, each selected based on the specific demands of the application.

Frequency dependence of Dielectric constant:
Dielectric constant (ε_r) remains unchanged when the material is subjected to a dc voltage. But ε_r changes when the material is subjected to the influence of an ac voltage, the changes depend on the frequency of the applied voltage. In addition, ε_r becomes a complex quantity and is expressed as
$$\varepsilon_r^* = \varepsilon_r{'} - j\,\varepsilon_r{''}$$
 where $\varepsilon_r{'}$ and $\varepsilon_r{''}$ are the real and imaginary parts of the dielectric constant.
$\varepsilon_r{'}$ represents part of the dielectric constant that is responsible for the increase of capacitance.

$\varepsilon_r"$ represents the losses represents part of the dielectric constant that is responsible for the increase of capacitance.
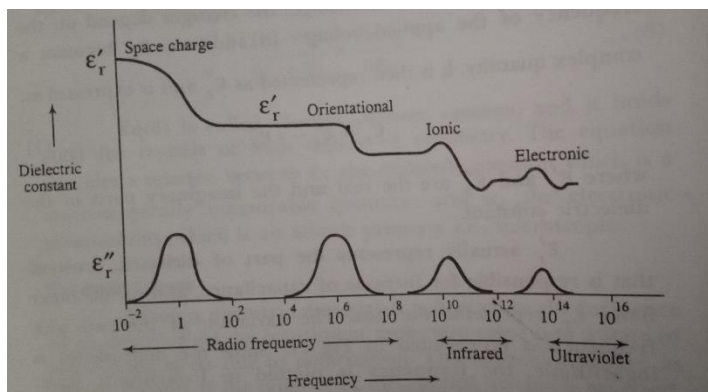

Figure 9: Variation of dielectric constant with frequency

All the four polarization mechanisms that occur in a dielectric material will be effective in static field conditions. But, each of them respond differently at different frequencies under alternating field conditions, since the relaxation frequency of different polarization processes are different as shown in figure 9. If τ_e, τ_i and τ_o are the relaxation times for electronic, ionic and orientation polarisations, then in general

$$\tau_e < \tau_i < \tau_o$$

When the frequency of applied field matches the relaxation frequency of a given polarisation mechanism, the absorption of energy from the field becomes maximum.

When the frequency of applied field becomes greater than the relaxation frequency for a particular polarisation mechanism, the switching action of the dipoles cannot keep in step with that of changing field and the corresponding polarization mechanism is halted. Thus, as the frequency of applied ac is increased, different polarization mechanisms disappear in the order- interface, orientation, ionic and electronic.

$$f_0 < f_i < f_e$$

The loss that occurs in a dielectric material is essentially due to the phase lag of voltage behind current in the capacitor between the plates of which dielectric material lies. Such a loss in a capacitor is expressed by a factor called tan δ. A large value of tan δ signifies higher dielectric loss. It is also referred to as tangent loss

$$\tan \delta = \frac{\varepsilon''_r}{\varepsilon'_r}$$

Dielectric Loss:

When a conductor is subjected to an AC/DC electric field, it dissipates part of the electrical energy into heat energy. Power loss denotes the average electrical power dissipated in a material during a certain interval of time; it is also called as I^2R loss or Joules heat.

This power loss (I^2R) in dielectrics is very small due to high resistance of dielectric materials to DC voltages and vice-versa to AC voltages. The absorption of electrical energy by a dielectric subjected to an alternating electric field is known as the dielectric loss. The origin of dielectric loss can be explained as follows:

"An AC field changes its direction with time. With each direction reversal, the molecules are required to follow the field reversals to contribute to the dielectric polarization." A capacitor once charged in one half-cycle, the molecules of the dielectric medium are polarized. When the capacitor is discharged in the second half cycle, the molecules revert to their initial condition. During this process of returning to their initial state, the molecules jostle with each other and lose energy due to friction. The energy lost due to friction takes the form of heat. This energy loss increases with increase in frequency.

Application of dielectrics

Dielectric materials are foundational to the design and operation of many electrical devices because they do not conduct electricity but can store electric energy through polarization. Their ability to resist current while supporting electrostatic fields makes them ideal for insulation and energy storage.

Capacitors:

Dielectrics are fundamental to capacitors, where they are inserted between conductive plates to increase capacitance. The dielectric material polarizes in the presence of an electric field, reducing the effective field strength and allowing the capacitor to store more charge for a given voltage. The type of dielectric used defines the capacitor's key characteristics.

Example: "Ceramic capacitors" (using a ceramic dielectric) are common in high-frequency circuits like radio transmitters and signal filtering due to their stability and low losses. "Electrolytic capacitors" (using a thin oxide layer dielectric) provide very high capacitance in a small package, making them ideal for storing energy and smoothing voltage ripples in power supplies for computers and amplifiers.

Transformers (Oils):

A transformer consists of two insulated coils wound on an insulated core. The amount of insulation to the coils and core are dependent on the voltage and hence in case of high voltage transformers insulation is required between individual windings of the coil and between the core and coils. The common materials used as insulation are paper, mica or cloth. The paper is impregnated with varnish or wax to fill the air gaps.

Since the permittivity of air is less, the chances of ionization at high voltages exists which ultimately leads to excessive heating and damage to the insulation. This effect is called as corona. Mica is used to guard against corona. For operating voltages greater than 3 kV and up, a kind of oil based on minerals known as transformer oil is used. The role of the oil is to not only keep the transformer

cool, but also guard against corona to upto 100 kV. A more conventional approach to keeping a large voltage transformer cool is by circulating cool water through it.

SF6 in High Voltage application:

In high-voltage applications, such as switchgear and circuit breakers, sulphur hexafluoride (SF_6) gas is employed for its exceptional insulating and arc-quenching properties. SF_6 is chemically stable, non-flammable, and has a dielectric strength much higher than air, allowing for compact and efficient designs. For example, SF_6 circuit breakers are used in 400 kV substations to safely interrupt fault currents and isolate equipment. However, SF_6 is a potent greenhouse gas, and its decomposition can produce toxic compounds, prompting the development of alternatives like fluoronitrile-based gases and vacuum interrupters.

SI No	Sample Questions and Numerical
1.	Define dielectric polarizability and dielectric susceptibility.
2.	Write differences between polar and non-polar dielectrics.
3.	Define polarization? Explain the four types of polarization.
4.	Discuss the frequency dependence of various polarization processes in dielectric materials.
5.	What do you mean by internal field? Derive Clausius-Mosotti relationship for cubic solids.
6.	Write short notes on dielectric loss. Show that dielectric loss is given by $\tan \delta = \varepsilon"_r / \varepsilon'_r$
7.	Calculate the dielectric constant of NaCl, if a NaCl crystal is subjected to an electric field of 1000 V/m and the resulting polarization is 4.3×10^{-8} C/m². **Solution:** $P = \varepsilon_0(\varepsilon_r - 1)E$ $(\varepsilon_r - 1) = \dfrac{P}{\varepsilon_0 E} = \dfrac{4.3 \times 10^{-8}}{8.856x10^{-12}x10^3} = 4.856$ $\varepsilon_r = 5.856$

8.	The dielectric constant of Helium at 0°C is 1.000074. The density of atoms is $2.7 \times 10^{25}/m^3$. Calculate the dipole moment induced in each atom when the gas is placed in an electric field of 3×10^4 V/m. **Solution:** Electronic polarizability $$\alpha_e = \frac{\varepsilon_0(\varepsilon_r - 1)}{N} = \frac{8.854 \times 10^{-12} \times 0.000074}{2.7 \times 10^{25}}$$ $$= 2.4255 x 10^{-41}$$ Dipole moment induced in each atom is $\alpha_e E$ $=2.4255 \times 10^{-41} \times 3 \times 10^4 = 7.2767 \times 10^{-37} Cm$
9.	An elemental solid dielectric material has a polarizability 7×10^{-40} Fm². Assuming the internal field to be Lorentz field, calculate the dielectric constant for the material if the material has 3×10^{26} atoms/m³. **Solution:** $$\frac{(\varepsilon_r - 1)}{(\varepsilon_r + 2)} = \frac{N\alpha_e}{3\varepsilon_0} = \frac{3 \times 10^{28} \times 7 \times 10^{-40}}{3 \times 8.854 \times 10^{-12}} = 0.7906$$ $$(\varepsilon_r - 1) = (\varepsilon_r + 2) \times 0.7906$$ $$\varepsilon_r = \frac{2.5812}{0.2094} = 12.33$$
10.	If the relative susceptibility of a material is 4.94 and the number of dipoles per unit volume is $10^{28}/ m^3$, calculate the polarizability of the material. **Solution:** Polarization $=N\alpha E$------(1) Relation between susceptibility and polarization is $P=\varepsilon_0 \chi E$-------(2) Equating these two equations, $\varepsilon_0 \chi E = N\alpha E$ $$\propto = \frac{\chi \varepsilon_0}{N} = \frac{8.854 \times 10^{-12} \times 4.94}{10^{28}} = 4.3738 \times 10^{-39} Fm^2$$
11.	The atomic weight and density of sulphur are 32 and 2.08 gm/cm³ respectively. The electronic polarizability of the atom is 3.28×10^{-40}F.m². If sulphur solid has cubic symmetry, what will be its relative permittivity? **Solution:** Clausius–Mossotti relation (valid for cubic symmetry)

$$\frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \frac{N\alpha}{3\varepsilon_0}$$

where N is the number density, α the atomic polarizability and $\varepsilon_0 = 8.854 \times 10^{-12}$F/m

Convert density and molar mass to SI and get N:ρ=2080kg/m³

$$M = 0.032kg \ /mol.$$

$$N = \frac{\rho N_A}{M} = \frac{2080 \times 6.022 \times 10^{23}}{0.032} == 3.91439 \times 10^{28} \text{ atoms/m}^3$$

Compute the right-hand side:

$$\frac{N\alpha}{3\varepsilon_0} = \frac{(3.91439 \times 10^{28})(3.28 \times 10^{-40})}{3(8.8541878 \times 10^{-12})} \approx 0.48336$$

Solve for ε_r:$\varepsilon_r = \frac{1+2x}{1-x}$ with $x = 0.48336$

$$\varepsilon_r = \frac{1 + 2(0.48336)}{1 - 0.48336} \approx 3.81$$

Content:

Magnetic Materials: *Classification of magnetic materials, Weiss Molecular field theory of ferromagnetism (Qualitative), Importance of Curie Temperature, Ferromagnetic Hysteresis and Explanation using Domain theory, Energy loss, Hard and soft ferromagnetic materials and Applications, Transformer Cores, Armature, Inductors and chokes, Permanent Magnets, Numerical Problems.*

Introduction

Magnetic materials play a prominent role in modern technology. They are widely used in electronics and computer industry. The methods of information storage and retrieval are based on magnetic storage techniques. Magnetic materials are substances, which upon being introduced into an external magnetic field, change so that they themselves become sources of an additional magnetic field. In 1845 Michael Faraday discovered that the magnetic materials can be broadly classified into three groups, namely diamagnetic, paramagnetic and ferromagnetic materials. The diamagnetic and paramagnetic materials are weakly magnetic and at any temperature they interact weakly with a magnetic field. Ferromagnetic materials interact strongly with a field at definite temperatures. The development of quantum physics helped us to understand the phenomenon of magnetism to a great extent. A large number of devices utilize mainly two magnetic phenomena, ferromagnetism and ferrimagnetism. The magnetic materials are classified into soft and hard materials. Soft magnetic materials are easily magnetized and demagnetized and are therefore used in ac applications. Hard magnetic materials retain magnetism on a permanent basis and are used in producing permanent magnets. These materials play an important role in information storage

devices. A basic understanding of the magnetic phenomena is essential to appreciate the operating principles of the various magnetic devices.

TERMS AND DEFINITIONS
To understand the behavior of magnetic materials and their applications, it is essential to study certain fundamental parameters. The following are some key magnetic parameters and their definitions.

Magnetic field -The space around a magnet where its magnetic influence is experienced is known as magnetic field.

Magnetic field intensity (H) - The magnetic field in which a material is kept is called magnetizing field. The strength (or intensity) of the magnetic field is denoted by H. The units of H are ampere-turns per metre (A/m) in SI system. Magnetic field is produced by permanent magnets such as a horse shoe magnet and temporarily by electromagnets. Intensity or strength of magnetic field at any point in a magnetic field is equal to the force experienced by a unit north pole placed at that point and is directed along the force.

Magnetization (M): The magnetic moment per unit volume developed inside a solid is called magnetization and is denoted by M. In SI system, M is measured in ampere per metre (A/m). Since the magnetization is induced by the field, we may assume that M is proportional to H.

$$\text{Thus, } M \propto H \text{ or } M = \chi H$$

where χ is the proportionality constant and is known as magnetic susceptibility.

Magnetic Susceptibility (χ): The magnetic susceptibility of a material is a measure of the ease with which the material can be magnetized. It is defined as magnetization produced in the material per unit applied magnetic field.

$$\text{Thus, } \chi = M / H$$

In general, the vectors M and H can have different directions and χ is a tensor. However, in isotropic media, M and H point in the same direction and χ is a scalar quantity. Materials having high susceptibility are easily magnetized.

Magnetic induction (B) –A magnetic field is schematically represented by lines of magnetic induction. It is described either by magnetic field strength H or by the magnetic induction (or magnetic flux density), B. The lines of induction are collectively called flux. Magnetic induction or magnetic flux density is defined as the total number of magnetic lines of force passing through unit area of cross section held normal to the lines of force, subjected to a uniform magnetic field.

$$i.e. \quad B = \frac{\phi}{A} \quad tesla \ or \ weber \ m^{-2}$$

The cgs unit for magnetic induction is the gauss (G). $1 \text{ G} = 10^{-4}$ T

Magnetization (M) – In a substance, atoms or molecules are randomly distributed. In the absence of external magnetic field, net dipole moment of the substance is zero. In an external field, nearly all the atoms or molecules (called magnetic dipoles) align themselves in the direction of the applied field. The substance acquires a net dipole moment. The substance is now said to be

magnetized. The process of magnetizing a substance is called magnetization.
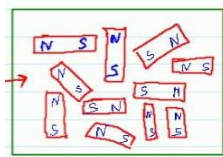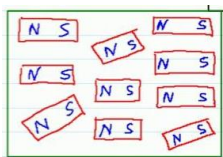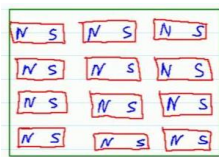
| **B=0** | **Weak B** | **Strong B** |

The dipole moment developed in a substance in external magnetic field per unit volume is called intensity of magnetization (M).

$$i.\,e.\ \ M = \frac{\mu_m}{v} = \frac{IA}{v} = \frac{IA}{Al} = \frac{I}{l} \qquad A\,m^{-1}$$

Magnetic permeability (μ) – It is defined as the ratio of number of lines of force passing per unit area held perpendicular to the lines of force in the specimen to the lines of force in the absence of specimen or it is defined as the ratio of magnetic induction to the strength of the magnetic field.

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

In free space, $B_0 = \mu_0 H$

$\mu_0 = 4\pi \times 10^{-7}\ Hm^{-1}$ is the permeability of free space.

Also, magnetic permeability of the medium is $\mu = \mu_0 \mu_r$

Permeability of any medium other than free space is called relative permeability (μ_r)

$$\mu_r = \frac{\mu}{\mu_0}$$

μ_r is the ratio of permeability in a material to that in free space. $\mu_r = 1$ for free space.

Relation between B, H & M

When a material is kept in a magnetic field, two types of induction arise: one due to the magnetizing field, H and the other as a consequence of the magnetization, M of the material itself. The magnetic induction, B, produced inside the material is given by

$$B = \mu_0 H + \mu_0 M \text{--------(1)}$$

$$or \quad B = \mu_0(H + M) = \mu_0 H\left(1 + \frac{M}{H}\right)$$

$$or \quad B = \mu_0 H(1 + \chi)\text{--------(2)}$$

where μ is called the absolute permeability of the medium. Like χ, μ is in general a tensor. In isotropic medium, it is a scalar quantity. In case of free space, M = 0 and equ. (1) reduces to B = μ$_0$H

If μ_r is the relative permeability of the medium then inside the medium, we also have

$$B = \mu H = \mu_0 \mu_r H \text{--------(3)}$$

From equations (1) and (3), we have

$$\mu_0 \mu_r H = \mu_0(H + M)$$
$$\mu_r H = H + M$$
$$M = H(\mu_r - 1)$$

Classification of magnetic materials

A material is magnetically characterized based on the way it can be magnetized. This depends on the material's magnetic susceptibility – its magnitude and sign. There are three basic magnetic materials are:

1. Diamagnetic materials
2. Para-magnetic materials
3. Ferro-magnetic materials (Anti-ferromagnetic materials and ferrimagnetic materials are considered as subclasses of ferromagnetic materials).

Diamagnetic material

Diamagnetic materials are the materials, when placed in a magnetic field, acquire feeble magnetism in a direction opposite to that of field. Inert gases, a majority of metals, and many organic compounds are diamagnetic substances. Examples: Hydrogen, air, water, gold, silver, and bismuth.

In general, diamagnetic materials do not have significant engineering applications. There is one special group known as superconducting materials, which are perfect diamagnetic materials. Their susceptibility is given by $\chi = -1$. This strong diamagnetism finds application in making frictionless bearings leading to a levitation effect.

Diamagnetism is a very weak form of magnetism that is induced by a change in the orbital motion of electrons due to an applied magnetic field. This magnetism is nonpermanent and persists only in the presence of an external field.

- Diamagnetism is also a property of all atoms because of the influence of an applied magnetic field on the motion of electrons in their orbits.
- The individual atoms of a diamagnetic material do not possess a permanent magnetic moment (Fig.1).
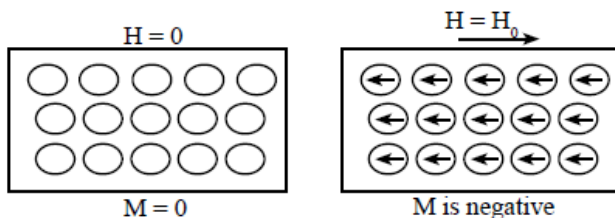

Figure 1: Magnetic dipole moment in diamagnetic material

- When an external magnetic field H_0 is applied, the atoms acquire a small induced magnetic moment in a direction opposite to the direction of the applied field (Fig.1). The strength of the induced magnetic moment is directly proportional to the applied field H_0. The induced dipoles and magnetization vanish as soon as the applied magnetic field is removed.

Properties of diamagnetic materials

- Permanent dipoles are absent. There is no permanent dipole moment
- They repel the magnetic lines of force.
- The magnetic susceptibility is negative ($\chi_m < 0$), i.e., magnetization opposes the applied field. The absolute value of susceptibility is small and is of the order of 10^{-6}.
- Magnetic susceptibility is independent of temperature and magnetic field strength.
- Relative permeability is slightly less than unity ($\mu_r < 1$).
- If suspended freely, they set themselves perpendicular to the field.

Paramagnetic materials

Paramagnetic materials are substances which when placed in a magnetic field acquire feeble magnetism in the direction of the magnetic field. Examples: Oxygen, solutions of iron salts, copper chloride, chromium and platinum.

In the absence of an external magnetic field, the individual atoms of paramagnetic material possess a permanent magnetic dipole moment of their own (Fig. 2).
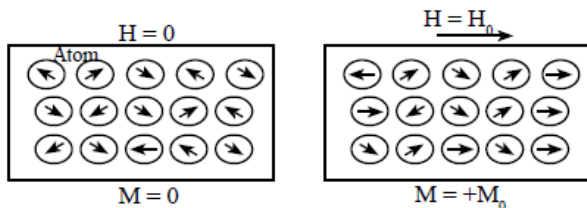
Figure 2: Magnetic dipole moment in paramagnetic material

- Each atom possesses a permanent magnetic moment.
- When $H = 0$, all the magnetic moments are randomly oriented because of the ceaseless random thermal motion of the atoms. So the magnetization $M = 0$.
- When an external magnetic field is applied, the magnetic dipoles tend to align themselves in the direction of the magnetic field (Fig. 2).

Properties of paramagnetic materials
- Paramagnetic materials possess permanent magnetic dipoles
- In the absence of an external applied field, the dipoles are randomly oriented. Hence the net magnetization in any given direction is zero.
- When placed inside the magnetic field, it attracts the magnetic lines of forces.
- Paramagnetic susceptibility is positive and depends on temperature. The susceptibility χ decreases with increase of temperature obeying the relation $\chi = C / T$ called the Curie's law, where C is constant and T is the temperature of the substance in absolute scale.
- The value of the paramagnetic susceptibility is independent of the applied magnetic field strength.

- When a rod is suspended in a magnetic field, the rod becomes parallel to the field.

Ferromagnetic materials

Ferromagnetic materials are metallic crystals which when placed in a magnetic field become strongly magnetized in the direction of the field. Examples: Iron, nickel and steel

- Ferromagnetic materials have a small amount of magnetization even in the absence of an external magnetic field. This indicates that there is a strong internal field within the material which makes the atomic magnetic moments align with each other (Fig.3).
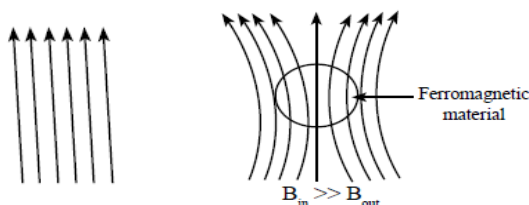

$B_{in} \gg B_{out}$

Figure 3: Magnetic dipole moment alignment in ferromagnetic material

- When placed in a magnetic field, ferromagnetic materials become strongly magnetized in the direction of the applied field (Fig.3).
- Ferromagnetism arises due to permanent magnetic moment in the atoms or molecules of the material. When an external field is applied, the magnetic moments lineup in the same direction as that of the applied field.

Properties of Ferromagnetic materials

- Ferromagnetic materials have permanent dipole moment. When placed inside a magnetic field, a ferromagnetic material attracts the magnetic lines of force very strongly.

- They exhibit magnetization even in the absence of the magnetic field.

- They exhibit the phenomenon of hysteresis. On heating they lose their magnetization slowly.

- The magnetic susceptibility of ferromagnetic materials is very high and depends on temperature. All ferromagnetic materials lose their ferromagnetism at a critical temperature called the Ferromagnetic Curie Temperature (θ). Above θ, the material behaves like an ordinary paramagnetic material and variation of χ obeys the relation, called Curie Weiss law.

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

Where T is the temperature of the substance in the absolute scale.

- The relative permeability of ferromagnetic materials is very high.

Comparison of Diamagnetic, Paramagnetic and Ferromagnetic materials

Property	Diamagnetic	Paramagnetic	Ferromagnetic
Magnetic moment	There is no permanent dipole moment	There is permanent dipole moment	There is enormous permanent dipole moment
Susceptibility and its temperature dependence	Susceptibility is always negative. It is independent of the temperature and strength of the magnetic field	Susceptibility is always positive. It is inversely proportional to absolute temperature of the material. $\chi = \frac{1}{T}$ or $\chi = \frac{C}{T}$	It is always positive and very large $\chi_m = \frac{C}{T-\theta}$ (i)For $T > \theta$, paramagnetic behavior. (ii)For $T < \theta$, ferromagnetic behavior.
Behavior of material in the presence of magnetic field	When the material is placed in the magnetic field, the magnetic lines of force are repelled away from the material. $B_{out} > B_{in}$	The magnetic lines of force are attracted towards the centre of the material. $B_{in} > B_{out}$	The magnetic lines of force are highly attracted towards the centre of the material. $B_{in} >> B_{out}$
Relative magnetic permeability	μ_r is slightly less than 1	μ_r is slightly greater than 1	μ_r is very much greater than 1.
Examples	bismuth, antimony, gold, Niobium	Aluminum, Platinum, Sodium, Titanium,	Iron, Nickel, Cobalt,

Weiss's molecular theory of Ferromagnetism

Weiss gave a theoretical explanation of the behavior of ferromagnetic materials. The theory is based on the following assumptions:

1. Weiss assumed that a ferromagnetic specimen contains a number of small regions (domains) which are spontaneously magnetized. The total spontaneous magnetization is the vector sum of the magnetic moments of the individual domain.

2. The spontaneous magnetization of each domain is due to the existence of an internal molecular field. This tends produce a parallel alignment of the atomic dipoles.

Weiss also assumed that the internal molecular field H_i is proportional to the magnetization M.

$$i.e., H_i = \gamma M$$

where γ is a constant called *Weiss constant*. If now an external field H acts on the dipole, then the effective field H_{eff} is given by

$$H_{eff} = H + H_i = H + \gamma M$$

In case of the paramagnetic state of a ferromagnetic material, the susceptibility is given by the expression

$$\chi = \frac{M}{H_{eff}} = \frac{C}{T}$$

Substituting for H_{eff} into the above equation, we find that

$$\chi = \frac{M}{H + \gamma M} = \frac{C}{T}$$

By rearranging the above equation, we get $\quad M = \frac{HC}{T - \gamma C}$

The magnetic susceptibility is:

$$\chi = \frac{M}{H} = \frac{C}{T - \gamma C} = \frac{C}{T - \theta}$$

Where, C is called *Curie constant* θ is called *Curie temperature*. The above equation is called the *Curie-Weiss law*.

- For values of temperature below Curie temperature (θ) the material shows ferromagnetic behavior.
- For values of temperature above θ, the ferromagnetic substance behaves like a paramagnetic substance.

B-H Hysteresis

When a ferro magnetic specimen is subjected to a magnetic field which varies cyclically, the magnetization of the specimen which is realized in terms of magnetic induction (B), fails to keep in step with the applied magnetic field (H). This property and its consequences are studied here.

Hysteresis is the phase lag of the magnetic induction (B) in ferromagnetic materials with respect to the cyclic variation of an applied magnetic field (H), when the specimen is below curie temperature.

Experimental arrangement is made in which a current passed through a long solenoid produces a magnetic field B, whose magnitude depends on the magnitude of current I and the number of turns N and its direction is in accordance with right thumb rule.
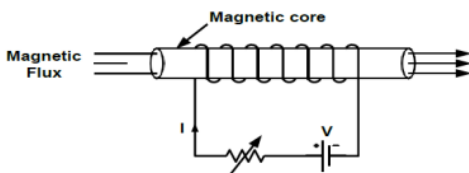
If a magnetizing material such as soft iron is kept inside the solenoid (of N turns and carrying the current I) and as the magnetizing field is increased by increasing the current by means of rheostat, the field inside the specimen increases according to the relation:

$$B = B_0 + B_m = \mu_0(H + M)$$

Thus, increasing magnetizing field H increases the magnetization and as a result increases the magnetic field B inside it. This is indicated by the curve OA in the graph of H vs B as shown in the Fig.4.
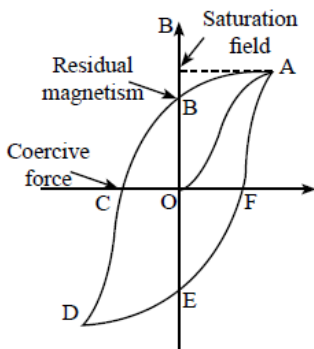

Figure 4: Hysteresis Curve

Beyond the point A, the field inside the specimen does not increase even H is increased. This field is called saturation magnetic field B_{sat}.

Now, the magnetic field is gradually decreased. The path is not retraced; the field is not becoming zero even when $H=0$. This is due to the magnetization of the specimen. The field retained in it is called residual magnetic field.

Now the direction of the current is reversed and the field H is gradually increased. Then B decreases and becomes zero for certain H. This field completely demagnetizes the specimen and is called coercive field (force).

If the field H is further increased, again the specimen attains saturation field at the point D. By gradually reducing H, we trace the path DE. Reversing the current and hence H, and increasing them we get the path EFA. Thus, a complete path in the form of a loop is got. This is called the cycle of magnetization. I t is observed that the specimen after attaining saturation point A, the field B inside it does not follow H. This lagging of magnetization behind the magnetizing field when a magnetizing material is subjected to the cycle of magnetization is called

"magnetic hysteresis". Lagging of B behind H and the magnetizing cycle is called Hysteresis loop.

The area enclosed by the loop is proportional to the energy lost per unit volume during one cycle of magnetization, which is dissipated as heat.

Significance of Hysteresis curves

The magnetic properties of a ferromagnetic substance can be obtained from the size and shape of the hysteresis loop. Figure shows the hysteresis loop for soft iron and steel.

(i) The resistivity of soft iron (OC) is greater than that of steel (OC'). i.e., soft iron retains more magnetism than steel, when the magnetizing force is totally removed.

(ii) The coercive force for soft iron (OD) is smaller than that for steel (OD'), i.e., iron is more readily demagnetized than steel.

(iii) The permeability $\mu = \frac{B}{H}$ for soft iron is greater than that of steel.

(iv) The susceptibility $\chi = \frac{M}{H}$ for soft iron is greater than that of steel.

(v) The area of the B-H loop for steel is much larger than that for soft iron. Thus, the energy loss per unit volume per cycle of magnetization is greater for steel than that for soft iron.
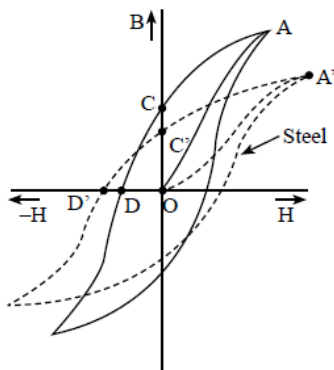
Domain theory of ferromagnetism

Weiss proposed the concept of domains in order to explain the properties of ferromagnetic materials. *The group of atomic dipoles organized into tiny bounded regions in the ferromagnetic materials are called ferromagnetic domains.*

Ferromagnetic materials contain a large number of domains. In demagnetized state, a ferromagnetic material is divided into number of small regions called *domains*. Each domain is spontaneously magnetized. The boundaries between different domains are called *domain walls*. The domain walls are also called *Bloch walls*.

In each individual domain, the magnetic moments of the atoms are aligned in the same direction. Hence the domain is a region of the ferromagnetic material in which all the magnetic moments are aligned to produce a net magnetic moment in one direction only. Thus, it behaves like a magnet with its own magnetic moment and axis.

In a demagnetized ferromagnetic material, the domains are randomly oriented (Fig. 5). So, the magnetization of the material as a whole is zero.
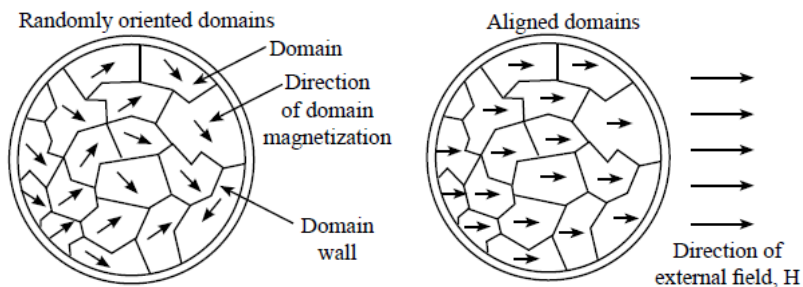

Figure 5: Random and aligned magnetic moments of the domains

When an external magnetic field is applied to a ferromagnetic material, then the domains align themselves in the direction of the magnetic field (Fig. 5). This results in a large net magnetization of the material.

A ferrimagnet has a spontaneous magnetic moment – a magnetic moment even in zero applied magnetic field. The existence of a spontaneous moment suggests that electron spins and magnetic moments are arranged in a regular manner as shown in Fig. 6.
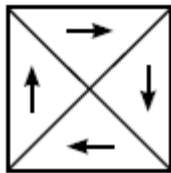

Figure 6: single crystal domain

Weiss introduced the concept of ferromagnetic domains. He postulates that any specimen consists of a large number of small regions or domains which are spontaneously magnetized. In the demagnetized state, the magnetization vectors of these domains are oriented in such a way that the specimen does not possess a resultant magnetic moment. Fig. 6 shows a single crystal domain arrangement for zero resultant magnetic moment.

When an external magnetic field is applied, the magnetization takes place either by domain wall movements or by rotation of domains.
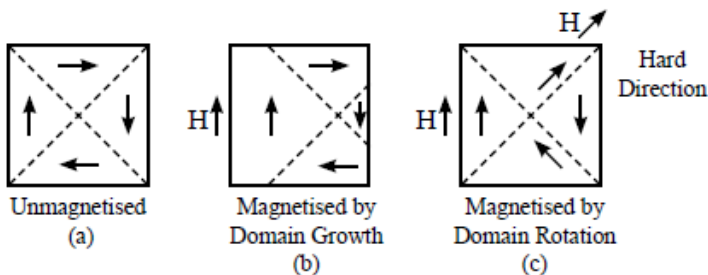

Figure 7: Domains response to the field

The increase in the gross magnetic moment of a ferromagnetic specimen in an applied magnetic field takes place by two independent processes.

(i) *By the motion of Domain wall*: In weak fields, the volume of domains (Fig.7) favorably oriented with respect to the field increases at the expense of unfavorably oriented domains. The magnetization changes by means of domain boundary displacements and so the domains change in size.

(ii)*By rotation of domains*: In strong applied fields, the domain magnetization rotates toward the direction of the field (Fig.7). For a very strong field, the magnetic moments of each and every domain undergo required amount of rotation so as to align precisely along the field direction of the field. Which indicates the ultimate stage of magnetization. This state of magnetization is called **saturation** beyond which further increase in magnetization is impossible, no matter how strong the filed is.
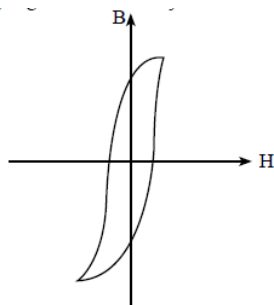
Soft magnetic materials
Magnetic materials that give rise to smaller area of hysteresis loop are called soft magnetic materials.
Ex: Fe – Ni alloy, Fe – Si alloys, Al – Si – Fe alloys, etc.
Properties

1. Easy to magnetize and demagnetize since domain wall movement is easier.
2. Hysteresis loop is thin and small.
3. Coercivity and retentivity are small.
4. Susceptibility and permeability values are very high.
5. Resistivity is very high, hence eddy current loss is very low.

Applications
Soft magnetic materials are used in the manufacturing of
1. Transformer cores, motors, relays and sensors, storage components, micro-wave isolators, electromagnets.
2. Electrical equipments, high frequency rotating materials, etc.

Hard magnetic materials
Magnetic materials that give rise to a larger area of hysteresis loop are called hard magnetic materials.
Ex: Cu – Ni – Fe alloy, Cu – Ni – Co alloys, Sm – Co alloy, etc.
Properties
1. Hard to magnetize and demagnetize.
2. Hysteresis loop is large and hence loss is more.
3. Coercivity and retentivity are large.
4. Susceptibility and permeability values are low.
5. Eddy current loss is very high.
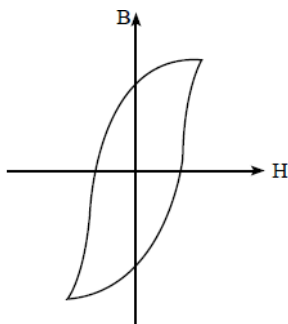
Applications
Hard magnetic materials are used in the manufacturing of
1. Permanent magnets, dynamos, motors, generators, galvanometers, ammeters, voltmeters, tape recorders, TV tubes, etc.
2. Microphones, speedometers, sensors in automobiles, etc.

Applications of Magnetic Materials

Magnetic materials find wide applications in electrical machines and devices.

Transformer cores are made of soft ferromagnetic materials such as silicon steel. These materials provide a low-reluctance path for magnetic flux and allow efficient magnetic coupling between the primary and secondary windings. To reduce eddy current losses, the cores are laminated.
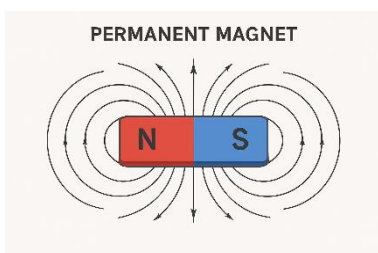

Primary   Secondary
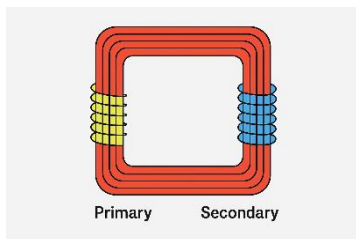
Armature cores, used in motors and generators, are also made of laminated soft iron or silicon steel. Their high permeability ensures strong flux linkage, while lamination reduces eddy current heating. This allows efficient electromagnetic interaction between the conductors and the field, producing torque (in motors) or emf (in generators).

Armature core
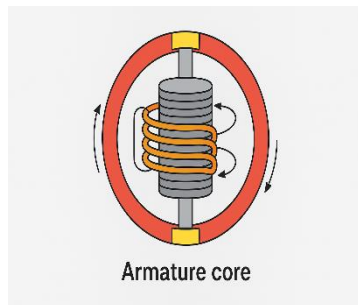
Inductors and chokes employ soft ferrites and laminated iron cores. Inductors store magnetic energy when current flows, while chokes are designed to block alternating current but allow direct current to pass. Soft ferrites are preferred in high-frequency applications due to their high resistivity, which minimizes eddy current loss.

INDUCTOR

Ferrite or laminated iron core
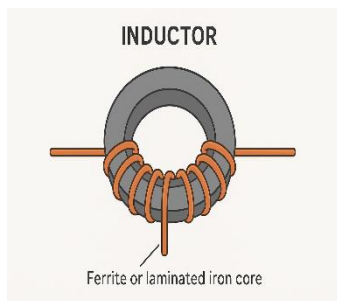
Permanent magnets are made of hard ferromagnetic materials such as hardened steel, Alnico alloys, ferrites, and rare-earth magnets (Nd–Fe–B, Sm–Co). These materials are characterized by high retentivity and high coercivity, allowing them to retain

PERMANENT MAGNET

magnetization for long periods. Permanent magnets are widely used in devices such as electric motors, loudspeakers, magnetic locks, compasses, and memory storage.

Q.No	Sample Questions and Numerical
1.	Define magnetic flux density, B, magnetic field strength, H, and magnetization, M. How are they related to each other?
2.	Define magnetic susceptibility and permeability. Obtain the relation between them.
3.	Why diamagnetic materials have negative susceptibility?
4.	How do you distinguish between diamagnetic, paramagnetic and ferromagnetic materials?
5.	What are ferromagnetic materials? Discuss the importance of hysteresis curve.
6.	Explain important magnetic properties of ferromagnetic materials.
7.	Explain ferromagnetic hysteresis on the basis of domains.
8.	In a magnetic material, the field strength is found to be 10^6 A/m. If the magnetic susceptibility of the material is 0.5×10^{-5}, calculate the intensity of magnetization and the flux density of the material. **Solution:** Magnetic susceptibility $\chi = \frac{M}{H}$ Magnetization $M = \chi H = 0.5 \times 10^{-5} \times 10^6 = 5$ Magnetic flux density $B = \mu_0(M+H)$ $\quad\quad = 4\pi \times 10^{-7}(5 + 10^6) = 1.257 \text{Wb/ m}^{-2}$

9.	A paramagnetic material has 10^{28} atoms/m³. Its magnetic susceptibility at 350K is 2.8×10^{-4}. Calculate the susceptibility at 300K. **Solution:** We know that $\chi = \frac{C}{T}$ where C is Curie constant $\therefore \frac{\chi_1}{\chi_2} = \frac{T_2}{T_1}$ Given $\chi_1 = 2.8 \times 10^{-4}$, $T_1 = 350K$, $T_2 = 300K$ $\chi_2 = \chi_1 \times \frac{T_1}{T_2} = 3.267 \times 10^{-4}$
10.	A magnetic material has a magnetization of 2300A/m and produces a flux density of 0.00314 Wb/m^{-2}. Calculate the magnetic field intensity and the relative permeability of the material. **Solution:** Magnetic flux density $B = \mu_0(M+H)$ Rearranging the above equation, we get Magnetic field intensity $H = \frac{B}{\mu_0} - M = \frac{0.00314}{4\pi \times 10^{-7}} - 2300 = 200$ A/m The relation between M, H and μ_r is $$M = H(\mu_r - 1)$$ Rearranging the above equation, we get $$\mu_r = \frac{M}{H} + 1 = \frac{2300}{200} + 1 = 12.5$$

11.	Given the Curie temperatures for Cobalt 1400 K and Iron 1000K, find the ratio of their magnetic susceptibilities at a temperature of 1600K. (Assume Curie constants are equal for Co and Fe). **Solution:** $T_C(\text{Co}) = 1400$ K, $T_C(\text{Fe}) = 1000$ K, Curie constants are equal $\Rightarrow C_{\text{Co}} = C_{\text{Fe}} = C$ **Magnetic susceptibility of Cobalt** $$\chi_{\text{Co}} = \frac{C}{1600 - 1400} = \frac{C}{200}$$ **Magnetic susceptibility of Iron** $$\chi_{\text{Fe}} = \frac{C}{1600 - 1000} = \frac{C}{600}$$ **Ratio of susceptibilities** $$\frac{\chi_{\text{Co}}}{\chi_{\text{Fe}}} = \frac{C/200}{C/600} = \frac{600}{200} = 3$$
12.	For a material obeying the Curie–Weiss law, take Curie constant is 0.0065 and Curie temperature is 300K. Compute (a) magnetic susceptibilty at 350K (b) magnetic susceptibilty at 400K (c) the ratio of susceptibilities. **Solution:** $\chi = \frac{C}{T - \theta}$ $$\chi_{350} = \frac{0.0065}{350 - 300} = \frac{0.0065}{50} = 1.3 \times 10^{-4}$$ $\chi_{400} = 6.5 \times 10^{-5}$ Calculation of ratios $\boxed{\dfrac{\chi_{350}}{\chi_{400}} = 2}$