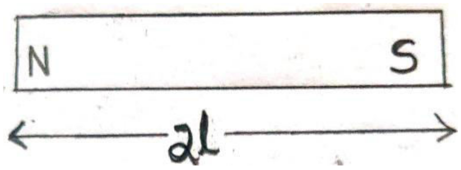
Introduction: Magnetism is a phenomenon by which a material exerts attractive or repulsive force on one another. When a magnet is freely suspended at any place on Earth's surface, it always comes to rest with its axis along north-south direction. This shows the existence of magnetic field at every point on Earth's surface. The magnetism of materials is a consequence of magnetic moment interactions of constituent atoms or molecules. Thus the materials that are magnetized when they are placed in magnetic field are called magnetic materials.

Basic Definitions of Magnetic Materials:

Magnetic Dipole:

Two equal and opposite magnetic poles separated by a small fixed distance is called magnetic dipole.



Magnetic Dipole

Magnetic dipole moment:

The product of pole strength and length of the magnet is called magnetic dipole moment.

$M = 2lm$ unit: Ampere-m^2

Magnetic field: The space around a magnet where its magnetic influence experienced is called magnetic field.

Magnetic Field Intensity:

The force experienced by unit north pole placed at a point in a magnetic field is called magnetic field intensity. It is a measure of magnetizing field. If F is the force experienced by a unit north pole placed at a point in magnetic field and *m* is the pole strength of the magnet then,

$$H = \frac{F}{m}$$ Unit: Ampere/ meter

Magnetic flux ϕ:

The total number of magnetic lines of force passing normally through a surface is called magnetic flux. Units: Weber or telsa/m^2

Magnetic flux density *B*:

The number of magnetic lines of force passing normally through a surface of unit area is called magnetic field induction or magnetic flux density.

$B = \frac{\phi}{A}$ It is a vector quantity. Units: Weber/meter^2

Intensity of magnetization *I*:

The magnetic moment per unit volume of the material is called the intensity of magnetization. If *M* is the magnetic moment and *V* is the volume of the magnet then the intensity of magnetization is $I = \frac{M}{V}$

If *m* be the pole strength, $2l$ is the length of the magnet and *A* is the area of magnet then, \

$$I = \frac{m \times 2l}{A \times 2l} = \frac{m}{A}$$

The intensity of magnetization is defined as pole strength per unit area. Units: Ampere/meter

Magnetic Susceptibility:

The intensity of magnetization produced in a material is directly proportional to the magnetizing field *H*

$$I \propto H \Rightarrow I = \chi H \Rightarrow \chi = \frac{I}{H}$$

Here, χ is known as magnetic susceptibility.

The susceptibility of magnetic material is a measure of the capacity of the material to acquire magnetization.

Magnetic permeability:

When a magnetic material is placed in a magnetic field it acquires magnetism due to induction. The lines of force of the magnetizing field concentrate inside the material and this results in the magnetizing of the material. The measure of degree to which force can penetrate into the medium is called permeability of the medium.

The magnetic flux density B is directly proportional to magnetic field intensity H

$$B \propto H \Rightarrow B = \mu H \Rightarrow \mu = \frac{B}{H}$$

Here, μ is constant of proportionality known as permeability of medium.

The magnetic flux density in air or vacuum is,

$$B_0 = \mu_0 H$$

Here, $\mu_0 = 4\pi \times 10^{-7}$ Henry/metre is the permeability of air or vacuum.

Magnetization:

The magnetic moment per unit volume developed inside a solid is called magnetization. It is the process of converting a non-magnet into a magnet. Two types of magnetic lines of force arises, one due to magnetizing field H and the other is due to intensity of magnetization.

$$B = B_0 + B_I = \mu_0 H + \mu_0 I = \mu_0 (H + I)$$

Relation between relative permeability and magnetic susceptibility:

Magnetic flux density in terms of magnetic field intensity is

$$B = \mu H \Rightarrow \mu_0 \mu_r H$$

The total flux density due to magnetic field intensity and intensity of magnetization is

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

$$\mu_0 \mu_r H = \mu_0 (H + I) \Rightarrow \mu_r = \frac{(H + I)}{H} = 1 + \frac{I}{H} = 1 + \chi$$

$$\mu_r = 1 + \chi$$

Origin of Magnetic Moment:

In atoms the permanent magnetic moment can arise due to the following factors

1. **The orbital motion of the electron:** The atom of any material consists of a central nucleus and the electrons move around the nucleus in specific orbit. Each electron orbit is equivalent to a tiny current loop and behaves as an elementary magnet having a magnetic dipole moment. The total orbital magnetic moment of an atom is the sum of orbital magnetic moments of individual electrons.

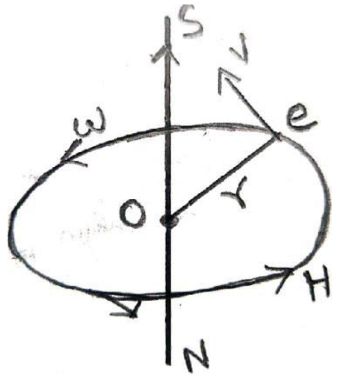
Consider an electron of charge e and mass m revolving around the nucleus in an orbit of radius r with an angular velocity

2. **The electron spin**: Each electron is spinning about an axis through itself and this spin also gives rise to a magnetic dipole moment.

3. **Nuclear spin**: In addition to electronic contribution nuclear spin also contributes to magnetic moment of atoms. Generally nuclear spin is very less in comparison with magnetic moment of an electron. Therefore we consider the resulting magnetic moment of an atom is the sum of the orbital and spin magnetic moments of the electron.

Orbital magnetic moment of electrons:

Consider an electron of charge e and mass m revolving around the nucleus in an orbit of radius r with an angular velocity ω as shown in figure. The circumference is $2\pi r$ and the area of the orbit is πr^2.



Magnetic Moment due to revolving electron

The linear velocity of the electron is, $v = r\omega$

The time period of the orbit is $T = \frac{\text{distance}}{\text{velocity}} = \frac{2\pi r}{v} = \frac{2\pi r}{r\omega} = \frac{2\pi}{\omega}$

The moving electrons circulate around nucleus in orbits are equivalent to current loops and produce magnetic fields. The current loop acts like a magnetic dipole and has certain value of magnetic moment.

The current in the orbit is, $i = \frac{e}{T} = \frac{e\omega}{2\pi}$

The magnetic moment of the electron, $\mu_{el} = i \times A = \frac{e\omega}{2\pi} \times \pi r^2 = \frac{e\omega r^2}{2}$

The angular moment of electron is, $L = mvr = mr^2\omega$

The ratio of magnetic moment to the angular momentum of the electron is known as gyromagnetic ratio.

$$\gamma_{el} = \frac{\mu_{el}}{L} = \frac{\frac{e\omega r^2}{2}}{mr^2\omega} = \frac{e}{2m}$$

The magnetic moment and angular momentum of electron are in opposite direction.

$$\mu_{el} = -\gamma_{el} \times L = -\frac{e}{2m} \times L$$

According to modern atomic theory, the angular momentum of electron is $L = \frac{lh}{2\pi}$

Here, l is the azimuthal quantum number.

The magnetic moment is $\mu_{el} = -\frac{e}{2m} \times \frac{lh}{2\pi} \Rightarrow -\frac{ehl}{4\pi m} = -\mu_B l$

Here, μ_B is the Bohr Magneton.

Spin magnetic moment of the electron:

An electron circulate around positively charged nucleus also rotates about its own axis. The magnetic moment associated with electron is spin magnetic moment.

$$\mu_{es} = \gamma_{es} \frac{e}{2m} S$$

Here, γ_{es} is known as spin gyromagnetic ratio which depends on the spinning of electron and its charge distribution.

Spin magnetic moment of Nucleus:

The magnetic moment produced by spin of the nucleus is nuclear spin magnetic moment.

$$\mu_{ps} = \frac{eh}{4\pi m_p}$$

Classification of magnetic materials:

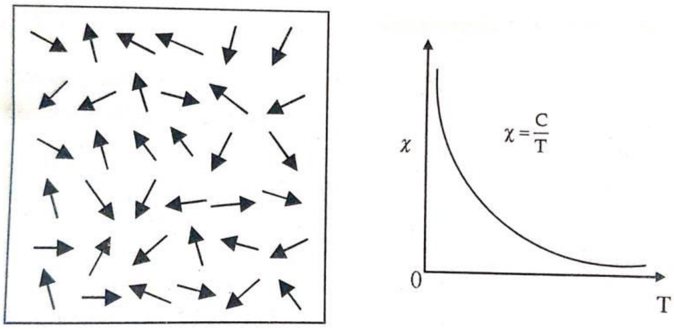
All materials can be classified in terms of the existence of permanent dipoles and their orientation into five categories depending on their bulk magnetic susceptibility. They are diamagnetic, paramagnetic, ferromagnetic, anti-ferro magnetic and ferri magnetic.

Diamagnetic Materials:

Diamagnetic Materials are the materials which have a weak magnetic moment that opposes applied magnetic field. It is the property of a material in which the number of dipoles and their orientation is such that the vector sum of magnetic moment is zero.

Paramagnetic Materials:

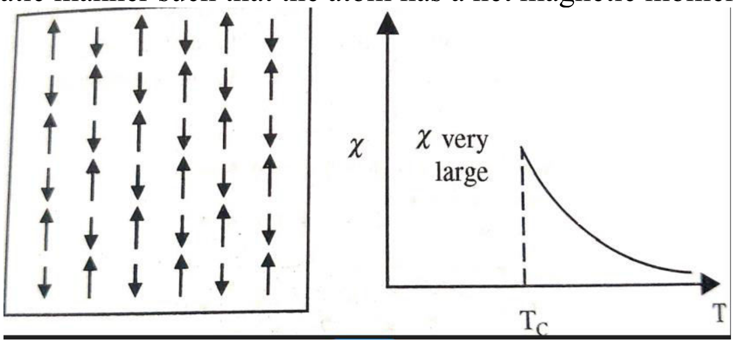
Para magnetic Materials are the materials which have a permanent magnetic moment in the direction applied magnetic field. It is the property of a material in which the number of dipoles and their orientation is such that the vector sum of magnetic moment is not zero.



Randomly oriented magnetic dipoles

Ferromagnetic Materials

Ferromagnetic Materials are the materials which have a strong magnetic moment in the direction of applied magnetic field. It is the property of a material in which all the orbits are oriented in systematic manner such that the atom has a net magnetic moment.



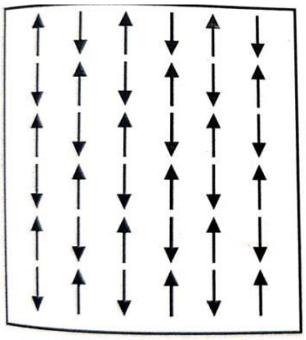
Orderly oriented magnetic dipoles

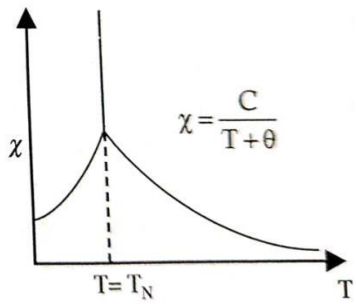
S. No	Diamagnetic	Paramagnetic	Ferromagnetic
1.	These are weakly magnetized in the direction opposite to the	These are weakly magnetized in the direction of the applied field direction.	These are strongly magnetized in the direction of the applied field

	applied field direction.		direction.
2	These are repelled by the magnets	These are weakly attracted by the magnets	These are strongly attracted by the magnets
3	There is no permanent dipole moment.	There is a small & finite dipole moment.	There is a large & permanent dipole moment
4	No spin alignment is present.	All spins are randomly oriented.	All spins are regularly oriented.
5	Relative permeability $\mu_r = 1$	Relative permeability $\mu_r > 1$	Relative permeability, $\mu_r >> 1$
6	Magnetic susceptibility χ is small and negative.	Magnetic susceptibility χ is small and positive.	Magnetic susceptibility χ is large and positive.
7	Magnetic field induction of this material is greater outside than inside, $B_{out} > B_{in}$	Magnetic field induction of this material is greater inside than outside, $B_{in} > B_{out}$	Magnetic field inside the material is very much greater than outside, $B_{in} >> B_{out}$
8	Susceptibility is independent of temperature.	Susceptibility varies with temperature as $\chi = \frac{C}{T}$	Susceptibility varies with temperature as $\chi = \frac{C}{T - T_C}$
9	Ex: Cu, Au, Bi, Hg, Si, Ge	Ex: Al, Pt, Mn, Cr, $CuCl_2$	Ex: Fe, Co, Ni, Dy, Gd

Anti-Ferromagnetic materials

Anti-Ferro magnetic materials are the materials which have zero net magnetic moment due to neighboring spins in opposite direction. It is the property of a material in which the number of dipoles and their orientation is such that the vector sum of magnetic moment is zero.





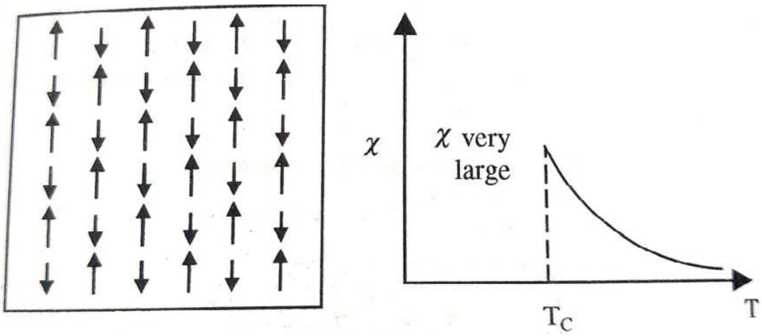
Anti-parallel alignment of magnetic dipoles with equal magnitude

Properties:

- The atomic dipoles are antiparallel to one another, so that net magnetization is zero.
- These materials exhibit *n* positive susceptibilities.
- χ changes with temperature, $\chi_{af} = \frac{C}{T + T_N}$
- The temperature at which anti ferro magnetic material changes to paramagnetic is called Neel's temperarture
- They attain maximum susceptibility at Neel's temperature. Ex: Mno, FeO, $MnCl_2$, $FeCl_2$

Ferri magnetic Materials

Ferri magnetic Materials are the materials which have net magnetic moment due to unequal magnitude of neighboring spins in opposite direction. It is the property of a material in which the number of dipoles and their orientation is such that the vector sum of magnetic moment is zero.

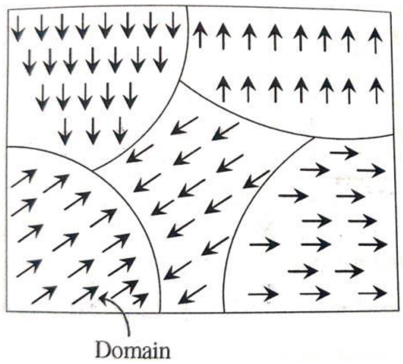


Anti-parallel alignment of magnetic dipoles with unequal magnitude

- All spins are anti-parallel to one another but unequal magnitude
- These exhibit a large magnetic susceptibility but depend on magnetic field.
- χ changes with temperature, $\chi = \dfrac{C}{T \pm T_N}$
- The material is ferri magnetic below Neel's temperature and paramagnetic above Neel's temperature
- Ferrites have chemical formula M^{2+}, Fe_2O_4 (M is divalent metal ion) Ex: Fe_3O_4, $NiFe_2O_4$

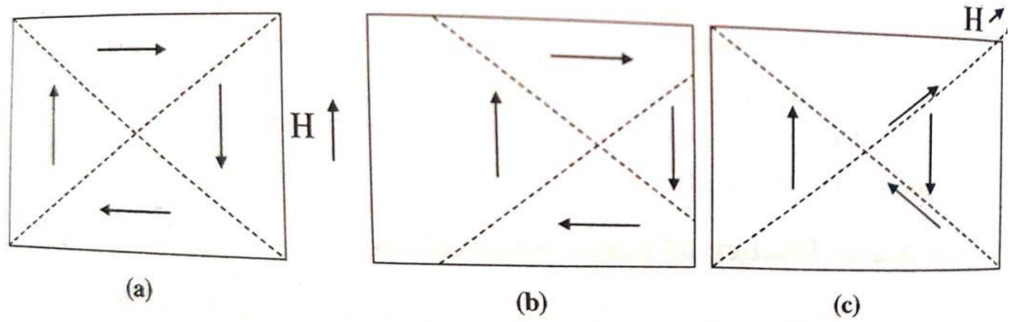
Domain theory of Ferromagnetism:

Ferromagnetic materials acquires strong magnetization with the magnetic moments of individual atoms interact individually and align themselves spontaneously. The atoms in these materials form a large number of small effective regions due to their mutual interaction. These regions are called Domains. Each domain has a size of order of $10^{-9} - 10^{-5}$ m^3 and contains about $10^{17} - 10^{21}$ atoms .The magnetic moments in the domains are arranged in the same direction due to exchange of coupling forces between them. This occurs even in the absence of external magnetic field. Every domain has net magnetic moment. Magnetic moments of different domains are randomly distributed hence the resultant magnetic moment in any direction is zero. The domains are separated by boundaries called "bloch walls" or "domain walls"



Magnetic domains in ferromagnetic material

When an external magnetic field is applied to a ferromagnetic material magnetization takes place in ways. ***1.*** **By domain growth**: When a specimen is placed in a magnetic field, the domains which are oriented in the direction of external field grow in size and expand into other domains that are in field direction. This is known as domain growth. This results in finite magnetization and takes place in weak external field

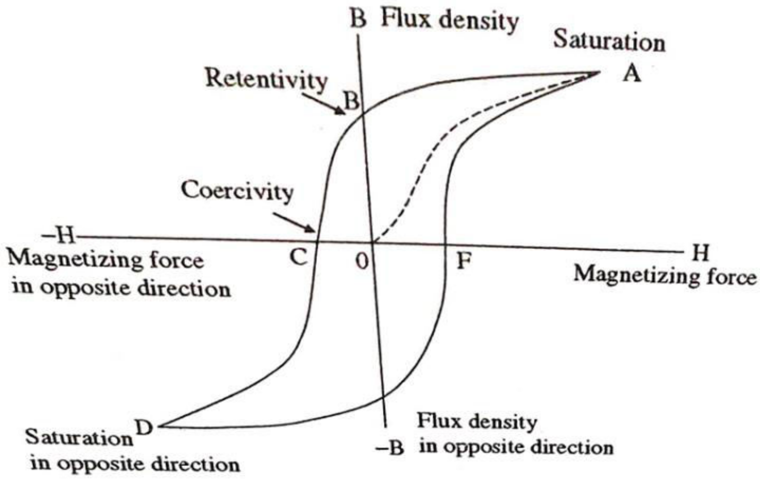


(a)Unmagnetized *(b) Domain Growth* *(c) Domain Rotation*

2. **By domain rotation**: When strong magnetic field is applied to domain rotates until their magnetic moments are aligned more or less in the direction of external field. When the domain vectors become parallel to the field, this results in saturation. Then the boundaries do not move completely to their positions and hence will not demagnetize completely. At higher temperature the domains will be broken and a ferromagnetic material becomes paramagnetic.

Hysteresis Loop or B-H loop or I-H loop or B-H curve or I-H curve:

Hysteresis loop is defined as the lag in the change of magnetization behind the variations of magnetic field. In magnetic materials the induced magnetic flux density B of a material lags behind the magnetizing field H.



Hysteresis Loop of Ferromagnetic Material

Consider a un magnetized ferromagnetic material and place it in a magnetizing field. The material is slowly magnetized from zero to high values with the increase of magnetizing field H, the magnetic flux density increases and reaches saturation at A.

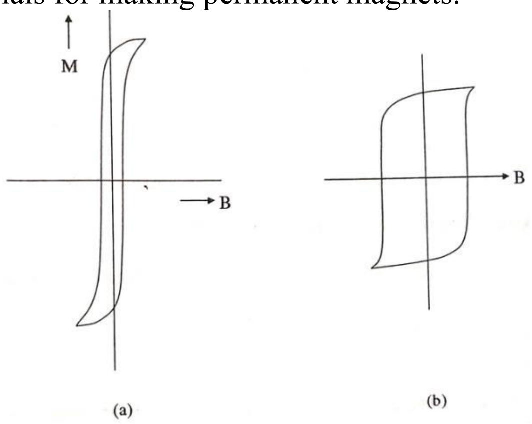
When H decreases, B decreases but does not come to zero at H=0. At this point some magnetic flux remains even if H=0. The magnetic flux is called residual magnetic flux. The property of magnetic materials in which magnetic flux density remains even when the applied field is reduced to zero is known as retentivity.

To bring B to zero opposite magnetizing field ($^{-}$H) is applied. As a result the curve moves to C (B=0). The magnetizing field represented by OC is called coercivity. As the magnetizing field is increased in negative direction it reaches saturation point D. Increasing H back in positive direction will return to point A along the path DEFA.

The loop OABCDEFA is called Hysteresis loop. The area of the loop gives the loss of energy due to the cycle of magnetization and demagnetization. This is dissipated in the form of heat.

Soft and Hard Magnetic Materials:

Based on the degree of retentivity and coercivity the magnetic materials are classified as soft and hard magnetic materials. The material having thin loop is used to make soft magnetic materials used for making temporary magnets. The materials having thick loop is used to make hard magnetic materials for making permanent magnets.



Hysteresis Loop for (a)Soft magnetic materials (b) Hard Magnetic Materials

	Soft magnetic materials	**Hard Magnetic Materials**
1	These are easily magnetized and demagnetized	These are not easily magnetized and demagnetized
2	The domain wall movement is easy.	The domain wall is difficult
3	These materials do not retain their magnetism after the removal of the applied magnetic field.	These materials retain their magnetism even after the removal of the applied magnetic field.
4	Retentivity and coercivity are small	Retentivity and coercivity are large
5	Permeability and susceptibility are large	Permeability and susceptibility are small.
6	Hysteresis loss is less due to small loop area	Hysteresis loss is high due to large loop area
7	Magnetostatic energy is small as it is free from irregularities.	Magnetostatic energy is small as it has irregularities.
8	Eddy current losses are more due to small retentivity.	Eddy current losses are less due to high retentivity.
9	Used in electric motors, generators, amplifiers, electromagnetic communication equipments. etc	Used in digital computers, ammeters, voltmeters, transformers, Dynamos, etc
10	Examples- Iron- silicon alloy, Ferrous nickel alloy, Ferrites, Garnets	Examples- Alnico, Chromium steel, tungsten steel, carbon steel

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Q. No		Assignment questions	Mar	CO	RBT
1	A	Explain about electronic polarization in atoms and obtain expression for electronic polarizability in terms of radius of the atom	8	CO3	Understand
	B	Define polarizability and write its units	2	CO3	Understand
2	A	Derive the relation among three electric vectors (D,E and P)	5	CO3	Understand
	B	Explain the dielectric loss and its importance.	5	CO3	Understand
3	A	Describe how the frequency dependence on polarizability.	6	CO3	Understand
	B	The hydrogen gas contains 9.7×10^{26} atoms/m ^{3} and the radius of atom is $0.52\ A^0$. Calculate the electronic polarizability.	4	CO3	Apply
4	A	Demonstrate the Orientational polarization in dielectrics.	4	CO3	Understand
	B	The hydrogen gas contains 9.7×10^{26} atoms/m ^{3} and the radius of atom is $0.52\ A^0$. compute the dielectric constant,	6	CO3	Apply
5	A	Describe about ionic polarization in dielectrics and derive the expression for ionic Polarizability.	7	CO3	Understand
	B	Argon gas contains 2.7×10^{26} atoms/m ^{3} at 0^0 C and 1 atm pressure. Calculate the dielectric constant if the diameter of argon atom is 0.384 nm	3	CO3	Apply
6	***A***	***Deduce the relation among three Magnetic Vectors (B,H & I)***	***5***	***CO3***	***Understand***
	B	***Derive the relation between Dielectric constant and Electric susceptibility***	***5***	***CO3***	***Understand***
7	***A***	***How the magnetic moment is originated at atomic level. Describe it***	***6***	***CO3***	***Understand***
	B	***Find the relative permeability of a ferromagnetic material if a field of strength 220 amp/meter produces a magnetization of 3300 amp/m in it.***	***4***	***CO3***	***Apply***
8	***A***	***Compare the dia, para and ferro magnetic materials with examples***	***10***	***CO3***	***Understand***
9	***A***	***Differentiate the Soft & Hard Magnetic Materials***	***7***	***CO3***	***Understand***
	B	***A magnetic material has a magnetization of 3300 amp/m and flux density of 0.0044 Weber/m². Calculate the magnetizing field. (*** $\mu_0 = 4\pi \times 10^{-7}$ Henry/metre ***)***	***3***	***CO3***	***Apply***
10	***A***	***Draw the Hysteresis Curve and explain its significance***	***7***	***CO3***	***Understand***
	B	***Determine the relative permeability of a ferromagnetic material if a field of strength of 200 amp/meter produces a magnetization of 3300 amp/m in it.***	***3***	***CO3***	***Apply***

Q. No	Viva questions from Unit-3	Mar	CO	RBT
1	What is meant by electric dipole moment? Write its units.	2	CO3	Understand
2	Define Electric Polarization. Write its expression.	2	CO3	Understand
3	What do you mean by dielectric Constant? Write its expression	2	CO3	Understand
4	Deduce the relation between three electric vectors.	2	CO3	Apply
5	Realize the relation between dielectric constant and electrical	2	CO3	Apply

	susceptibility			
6	Describe electronic & ionic polarizations	2	CO3	Understand
7	Explain the Langevin-Debye Equation for total polarizability	2	CO3	Understand
8	Explicate Orientational Polarizability. Write its expression	2	CO3	Understand
9	***Describe the magnetic dipole moment? Write its units.***	***2***	***CO3***	***Understand***
10	***Discriminate Hard & Soft Magnetic materials.***	***2***	***CO3***	***Understand***
11	***Work out the relation between three magnetic vectors.***	***2***	***CO3***	***Apply***
12	***How the magnetic materials are classified? List out them.***	***2***	***CO3***	***Understand***
13	***Mark any two properties of Anti-Ferro magnetic materials***	***2***	***CO3***	***Understand***
14	***Write any two properties of ferrimagnetic materials***	***2***	***CO3***	***Understand***
15	***Draw the B-H curve and Label it***	***2***	***CO3***	***Apply***

Numerical Problems on Unit-3
The hydrogen gas contains 9.7×10^{26} atoms/m ^{3} and the radius of atom is $0.52\ A^0$. Calculate the electronic polarizability.
Argon gas contains 2.7×10^{26} atoms/m ^{3} at 0^0 C and 1 atm pressure. Calculate the dielectric constant if the diameter of argon atom is 0.384 nm
Find the relative permeability of a ferromagnetic material if a field of strength 220 amp/meter produces a magnetization of 3300 amp/m in it.
A magnetic material has a magnetization of 3300 amp/m and flux density of 0.0044 Weber/m^2. Calculate the magnetizing field. ($\mu_0 = 4\pi\times10^{-7}$ Henry/metr e ***)***
Determine the relative permeability of a ferromagnetic material if a field of strength of 200 amp/meter produces a magnetization of 3300 amp/m in it.