UNIT

3

Magnetic and Superconducting Materials

3.1 MAGNETIC MATERIALS

Introduction

Any material that can be magnetised by application of external magnetic field is called a magnetic material. *Magnetic materials* are substance upon which being introduced into an external magnetic field, they themselves become source of an additional magnetic field.

In 1845, Michel Faraday discovered that the magnetic materials can be broadly classified into three groups, namely diamagnetic, paramagnetic and ferromagnetic materials.

Magnetic materials play prominent role in modern technology. They are widely used in industrial electronics, entertainment electronics and computer industry. The development of quantum physics helped us understand the phenomenon of magnetism to a great extent. A large number of devices utilize mainly two magnetic phenomena, ferromagnetism and ferrimagnetisms.

A basic understanding of the magnetic phenomena is essential to appreciate the operating principles of the various magnetic devices. We know that current through a circular coil produces magnetic moment along the axis of the coil. When the electrons revolve around the positive nucleus, orbital magnetic moment arises. Similarly when the electron spins, spin magnet moment arises. Magnetism arises from the magnetic moment (or) magnetic dipole of the magnetic materials.

3.2 BASIC DEFINITIONS

i. Magnetic field :

The space around the magnet or current carrying conductor where the magnetic effect is felt is called Magnetic field. (Amp / m)

ii. Magnetic lines of force

Magnetic field is assumed to consist of lines of magnetic forces. These lines of forces seems to travel externally from north to south poles of the magnet as shown in Fig.3.1.

Hence a *magnetic lines of force* is defined as the continuous curve in a magnetic field. The tangent drawn at any point on the curve gives the direction of the resultant magnetic intensity at that point.

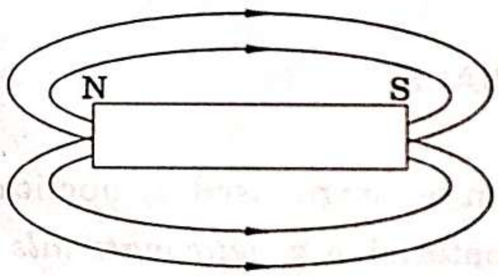


Fig. 3.1

iii. Magnetic flux (ϕ)

"The total number of magnetic lines of force passing through a surface" is known as magnetic flux. Its unit is Weber (Wb)

iv. Magnetic induction or Magnetic flux density (B)

"It is defined as the number of magnetic lines of force passing perpendicularly through a unit area of cross section". (Wb/m^2 or Tesla).

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

v. Magnetic field intensity (H)

It is defined as the force experienced by a unit north pole placed at that point in a magnetic field . Its unit is Am^{-1}.

It is also defined as the ratio between the magnetic induction (B) and the permeability of the medium in which magnetic field exists.

$$\vec{H} = \frac{\vec{B}}{\mu} \text{ Am}^{-1}$$

vi. Magnetic dipoles

It is defined as the system having two equal and opposite magnetic poles seperated by a small distance.

vii. Dipole moment

The dipole moment is defined as "the product of magnetic pole strength and length of the magnet".

dipole moment $\mu_m = m \times l$ Amp m^2

where, m - magnetic pole strength (Am)

l - length of the magnet.

or $\mu_m = IA$

where, I - electric current flowing through a circular wire of area of cross section (A).

viii. Intensity of Magnetisation or Magnetisation (I)

Magnetisation is the "process of converting non-magnetic into magnetic material. The intensity of magnetisation is defined as "the measure of the magnetisation in any magnetic material".

It can also be defined as the magnetic moment per unit volume.

i.e., $I = \frac{\mu_m}{V}$ Wb/m^2

ix. Magnetic susceptibility (χ_m) (chy)

It is defined as "the ratio of the intensity of magnetisation (I) produced to the applied magnetic field intensity (H)".

$$\chi_m = \frac{I}{H}$$

χ_m of a material is a measure of the ease with which the material can be magnetised.

x. Magnetic permeability (μ)

The magnetic induction B due to magnetic field Intensity H are directly proportional to each other.

$$B \propto H$$

$$B = \mu_0 H$$

where μ_0 - permeability of free space (vacuum) $4\pi \times 10^{-7}$ H/m.

If the field is applied in any medium of permeability μ then

$$B = \mu H$$

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

It is defined as the ratio between the magnetic flux density (B) and the applied magnetic field intensity (H).

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

It is the measure of degree at which the lines of force can penetrate through the material.

xi. Relative permeability (μ_r)

It is defined as "the ratio between the permeability of the medium to the permeability of free space".

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

Relation between μ_r and χ_m

When a magnetic material is placed in a magnetic field (H), then two types of lines of induction passes through the material.

(i) Due to magnetising field (H)

(ii) Due to material itself being magnetised by induction (I)

$\therefore$ Total flux density $\quad B = \mu_0 (H + I) \quad$ ... (1)

We know,

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

$$B = \mu H \quad \text{... (2)}$$

Equating equation (1) and (2) we get

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

Since $\quad \mu = \mu_0 \mu_r$

$$\mu_0 \mu_r H = \mu_0 H \left(1 + \frac{I}{H}\right)$$

$$\therefore \quad \mu_r = \left(1 + \frac{I}{H}\right) \qquad \left(\text{Since } \chi_m = \frac{I}{H}\right)$$

$$\mu_r = 1 + \chi_m$$

3.3 ORIGIN OF MAGNETIC MOMENTS

The macroscopic magnetic properties of a substance are a consequence of magnetic moments associated with individual electrons. Each electron in an atom has magnetic moments that originate from the following two sources.

i. Orbital magnetic moment of electrons.

ii. Spin magnetic moment of electrons.

Magnetic moments associated with an orbiting electron and a spinning electron is shown in Fig. 3.2 (a and b).

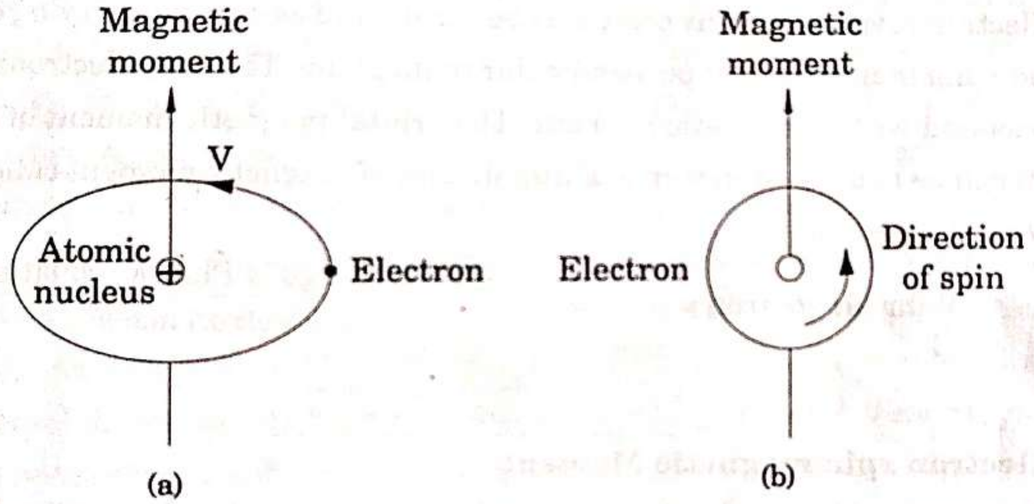


Fig. 3.2

We know that the electrons in an atom revolve around the nucleus in different orbits. Basically, there are three contributions for the magnetic dipole moment of an atom.

i. The *orbital motion of electrons* (the motion of electrons in the closed orbits around the nucleus). It is called as orbital magnetic moment. Its magnitude is always small.

ii. *Spin motion of the electrons* (i.e., due to electron spin angular momentum) and it is called as spin magnetic moment.

iii. The contribution from the *nuclear spin* (i.e., due to nuclear spin angular momentum). Since this is nearly 10^3 times smaller than that of electron spin, it is not taken into consideration.

For all practical purposes, we assume that the magnetic moment arises due to the electron spin ignoring the orbital magnetic moments and the nuclear magnetic moments as their magnitudes are small.

We may note that permanent magnetic moments can also arise from spin magnetic moments of the nucleus. Of all the three, the spin dipole moments of electrons are important in most magnetic materials.

(i) Orbital angular momentum of the e⁻s

This corresponds to a permanent magnetic dipole moments.

Let us consider an e⁻ describing a circular orbit of radius 'r' with a stationary nucleus at the centre as shown in Fig 3.3(a). Let the e⁻ rotate with a constant angular velocity of 'ω' radians per second.

Electron revolving in any orbit may be considered as current carrying circular coil producing magnetic field perpendicular to its plane. Thus the electronic orbits are associated with a magnetic moment. The orbital magnetic moment of an e⁻ in an atom can be expressed in terms of atomic unit of magnetic moment called *Bohr Magneton*, defined as

$$1 \text{ Bohr Magnetron} = \mu_B = \frac{\text{electron charge x Plancks constant}}{2 \text{ x Electron mass}}$$

$$\mu_B = \frac{e\hbar}{2m_e} = \frac{e}{m_e}\frac{h}{4\pi}$$

(ii) Electron spin magnetic Moment

The concept of the e⁻ having an angular momentum has been introduced in order to explain the details of atomic spectra. This angular momentum of the e⁻ is referred to as the spin of the e⁻. Since the e⁻ has a charge, its spin produces a magnetic dipole moment. According to quantum theory, the spin angular momentum along a given direction is either

$$\frac{+h}{4\pi} \text{ (or) } \frac{-h}{4\pi}$$

Hence the spin dipole moment components along an external field are

$\frac{e}{m}\cdot\frac{h}{4\pi} = +1$ Bohr magneton (or)

$-\frac{e}{m}\cdot\frac{h}{4\pi} = -1$ Bohr magneton.

In a many electron atom, the individual spin magnetic moments are added in accordance with certain rules. Completely filled shells contribute nothing to the resultant spin moment.

(iii) Nuclear Magnetic Moment

The angular momentum associated with the nuclear spin is also measured in units of $h/2\pi$. The mass of the nucleus is larger than that of an e^- by the order of 10^3. Hence nuclear spin magnetic moment is of the order of 10^{-3} Bohr magnetrons.

3.4 CLASSIFICATION OF MAGNETIC MATERIALS

Now we are going to study the various types of magnetic materials in terms of the magnetic properties of the atomic dipoles and the interactions between them. Very first distinctions is based on wheather the atoms carry permanent magnetic dipoles or not. Materials which lack permanent dipoles are called *Diamagnetic.*

If the atoms of the material carry permanent magnetic dipoles, such a material may be paramagnetic, ferromagnetic, antiferromagnetic or ferrimagnetic, depending on the interaction between the individual dipoles. If the permanent dipoles do not interact among themselves, the material is *Paramagnetic*. If the interaction among permanent dipoles is strong such that all the dipoles line up in parallel, the material is *Ferromagnetic.* If the permanent dipoles line up in antiparallel direction, the material is *Antiferromagnetic and Ferrimagnetic.*

In *antiferromagnetic* materials the magnitudes of permanent dipoles aligned parallel and antiparallel are *equal* and hence the magnetization vanishes.

In the case of *ferrimagnetic materials,* magnitudes of permanent dipoles aligned antiparallel are not equal thus exhibiting magnetization.

1. Materials not having permanent magnetic moment
   a) Diamagnetic materials
2. Materials having permanent magnetic moment
   a) Paramagnetic material (No interaction between dipoles)
   b) Ferromagnetic materials (Dipoles line up in parallel)
   c) Antiferro or Ferrimagnetic materials. (Dipoles line up in antiparallel)

3.4.1 Diamagnetism

"Materials which does not have permanent magnetic dipoles" are termed as Diamagnetic materials.

These materials repel the magnetic lines of force when external magnetic field is applied(Fig 3.4). In these materials there are even number of electrons and all the electrons which spin in two opposite directions are almost equal and so they cancel out and the net magnetic moment is zero. They do not have any permanent magnetic moment or dipoles in the absence of external magnetic field. But when the magnetic field is applied these electrons reorient themselves that they align opposite to the field direction and oppose the applied magnetic field. Hence, the magnetic induction is almost reduced. Diamagnetism is understood by the schematic illustration shown in Fig. 3.3 (a & b)

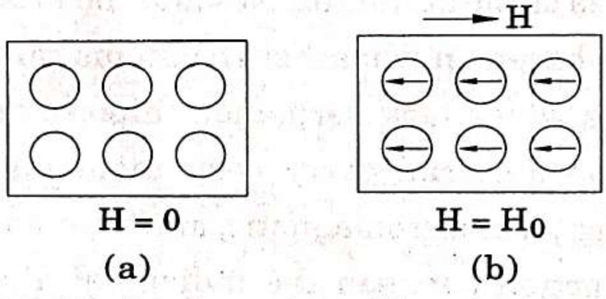


Fig. 3.3 Dipole orientation with and without field

When the magnetic field H is zero, the atoms possess zero magnetic moment Fig. 3.3(a). When a magnetic field is applied in the direction shown in Fig. 3.3(b), the atoms acquire an induced magnetic moment in the direction opposite to that of the field. The strength of the induced magnetic moment is proportional to the applied field and hence the magnetisation of the material varies linearly with the strength of the magnetic field. The induced dipoles and magnetisation vanish as soon as the applied field is removed.

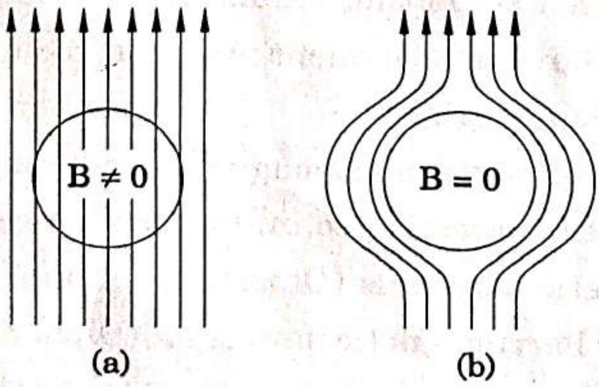


Fig. 3.4 Effect of Magnetic field in diamagnetic material

Properties

1. They repel the magnetic lines of force.
2. Susceptibility is negative and is independent of temperature and applied magnetic field strength.

3. The value of Permeability is less than 1.
4. No permanent dipole moments in the absence of magnetic field.
5. When temperature is less than critical temperature diamagnets become normal material.

Ex. Gold, Germanium, Silver, Lead, Copper, Silica, Organic materials, etc.,

3.4.2 Paramagnetism

In certain materials, each atom or molecule possesses a net permanent magnetic moment (due to the orbital and spin magnetic moments) even in the absence of an external magnetic field.

The magnetic moments are randomly oriented in the absence of an external magnetic field. This makes the magnetisation of the material nearly zero. ie., a little magnetisation is present within the material.

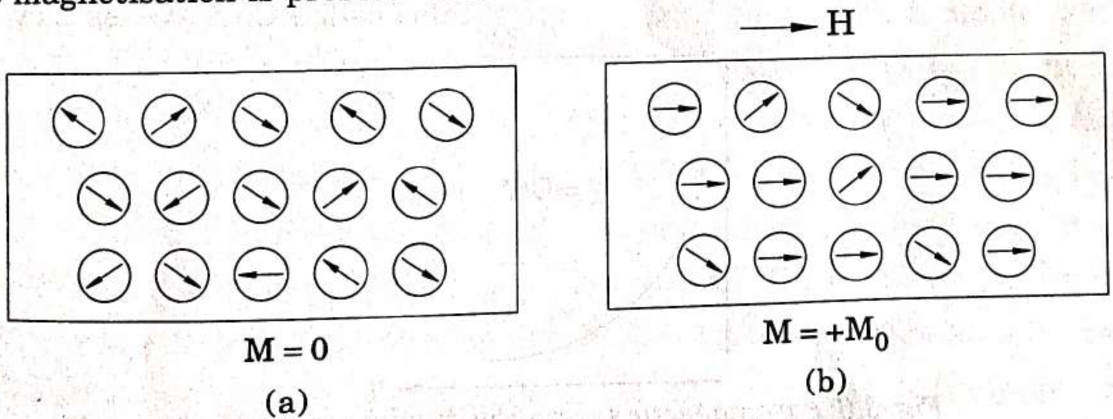


Fig. 3.5 Paramagnetic material.

(a) Each atom possesses a permanent magnetic moment. When H = 0, all the magnetic moments are randomly oriented; so M ≠ 0.

(b) When a magnetic field H_0 is applied, the magnetic moments tend to orient themselves in the direction of the field, resulting in positive susceptibility.

But, when an external magnetic field is applied, the magnetic dipoles tend to align themselves in the direction of the magnetic field and the material becomes magnetized. This effect is known as *Paramagnetism.* This is illustrated in Fig. 3.5 (a) and (b).

Thermal agitation disturbs the alignment of the magnetic moments. With an increase in temperature, the increase in thermal agitation tends to randomize the dipole direction thus leading to a decrease in magnetization.

This implies that the paramagnetic susceptibility decreases with increase in temperature. It is observed that the paramagnetic susceptibility varies inversely with temperature.

i.e.,

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

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

This is known as the *Curie Law of Paramagnetism* and 'C' is a constant called *Curie constant.*

Properties

1. Magnetic susceptibility is positive and it greatly depends on the temperature. It is given by

$$\chi = \frac{C}{T-\theta}$$ (also called Curie-Weiss Law)

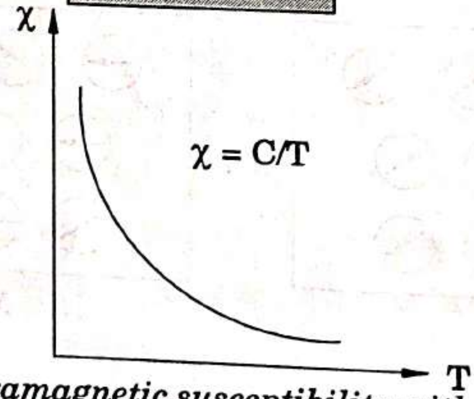


Fig. 3.6 Paramagnetic susceptibility with temperature

where

C - Curie constant, T - Absolute temperature, θ - Curie temperature

2. The magnetic lines of force pass through the material.

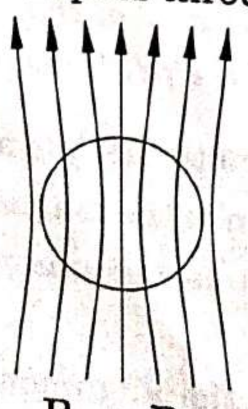


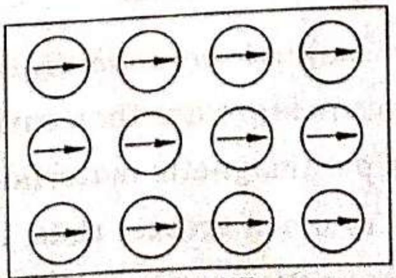
Fig. 3.7 Effect of Magnetic field in Paramagnetic Material

3. Since magnetic lines of force pass through the material, they posses permanent dipole moment which makes permeability greater than one.
4. Magnetic susceptibility is independent of applied magnetic field.
5. They possess permanent dipole moment.
6. When the temperature is less than curie temperature, paramagnetic material becomes diamagnetic material

   Examples : $CuSO_4$, $MnSO_4$, Platium, Chromium, $NiSO_4$, etc.

3.4.3 Ferromagnetism

There are certain substances like Fe, Ni, which have high degree of magnetisation inspite of their randomizing tendency of the thermal motions of atoms. These materials are called ferromagnetic and the phenomenon is called as Ferromagnetism. Eventhough the net spin magnetic moment of these materials are of the same order as that of a paramagnetic materials, still exhibits strong magnetisation. This is due to the *spontaneous magnetisation*. This occurs due to a special form of interaction called exchange coupling between adjacent atoms even in the absence of applied magnetic field coupling their magnetic moments together in rigid parallelism. When placed in a magnetic field it strongly attracts the magnetic lines of forces. It has a characteristic temperature called the ferromagnetic curie temperature θ_F. The permeability depends greatly on temperature. Above θ_F its properties are quite different, it behaves as a paramagnetic material. Spin alignment is parallel Fig. 3.8). These materials consists of number of small regions called *domains* which are spontaneously magnetised.



$H = H_0$

Fig. 3.8 Dipole arrangment in ferromagnetic material.

Properties

1. Since some magnetisation is already existing in these materials, all the magnetic lines of force passes through it.

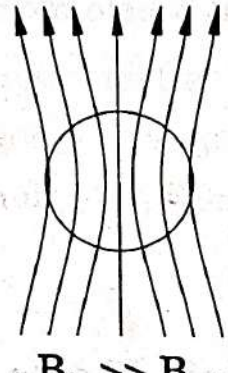


Fig. 3.9 Effect of Magnetic field in ferromagnetic Material

2. They have permanent dipole moment. So they act as strong magnets.
3. They exhibit magnetisation even in the absence of external field. This property is called Spontaneous magnetisation.
4. It's susceptibility is positive and high. Also it depends on temperature. Fig. 3.10.

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

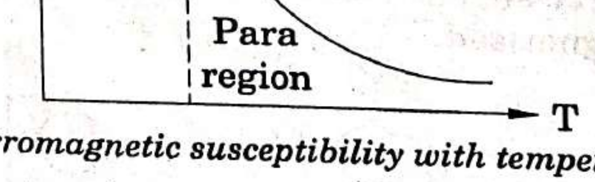


Fig. 3.10 Ferromagnetic susceptibility with temperature

5. When the temperature is greater than curie temperature, ferromagnetic material becomes paramagnetic material.
6. Permeability is very much greater than 1.
7. They exhibit magnetization even when the magnetising field is removed. Hence they exhibit magnetic hysteresis.

   Examples : Ni, Co, Fe etc.,

3.5 COMPARISON CHART FOR DIA, PARA AND FERRO-MAGNETIC MATERIALS

S.No.	Parameters	Diamagnetic material	Paramagnetic material	Ferromagnetic material
1.	Definition	It is a material in which there is no permanent dipole moment (or) magnetic moment in each atom. The external magnetic field decreases the magnetic induction present in the specimen.	It is a material in which there is permanent dipole moment in each atom. External magnetic field increases the magnetic induction present in the specimen.	It is a material in which there is enormous permanent dipole moment or magnetic moment in each atom. External magnetic field increases very large magnetic induction present in the specimen.
2.	Temperature dependence.	Independent of temperature.	It is inversely proportional absolute temperature.	It depend on temperature in a complex manner.
3.	Behaviour of material in the presence of external magnetic field.	When the external magnetic field is applied, the electrons will align perpendicular to the field direction and hence it reduces the magnetic induction present in the material. Thus they are name as **weak magnets.**	When the external magnetic field is applied, the electrons will align parallel to the field direction and hence the material is magnetised. Thus they are named **strong magnets.**	When the external magnetic field is applied, the electrons which are already aligned parallel will reorient itself along the field direction and will be very easily magnetised. Thus they are named as **very strong magnets.**
4.	Movement of magnetic flux lines	The magnetic lines of force are repelled away from the material and hence $B_{out} > B_{in}$	The magnetic line of force are highly attracted towards the centre of material and hence $B_{in} > B_{out}$.	The magnetic line of force are highly attracted towards the centre of material and hence $B_{in} >> B_{out}$.

5.	Spin alignment (or) Magnetic moment alignment.	No spin (or) Magnetic moment.	All spins or magnetic moments are randomly oriented.	All spins or magnetic moment are orderly oriented.
6.	Origin.	Arises from the larmor precession of electronic orbits in the presence of applied magnetic field.	Arises from the magnetic moments origination along the external magnetic field direction and magnetic moments orientation is largely determined by temperature and magnetic field.	A rises from the spontaneous magnetization due to local molecular magnetic field which arises from exchange interaction between unpaired electrons & adjacent atoms in the crystal lattice.
7.	Magnetic phase transition	When the temperature is greater than the critical temperature, the diamagnetism suddenly disappears and becomes a normal material.	When the temperature is greater than its curie temperature, it is converted in to a diamagnetic substance	When the temperature is greater than its curie temperature it is converted into paramagnetic.
8.	Permeability	Very less (μ_r<1)	High (μ_r>1)	Very high (μ_r >>1)
9.	Susceptibility	It is negative.	It is positive & small.	It is positive & large.
10.	Example	Hydrogen, Bismuth, Gold, Antimony, Germanium, Nioblum, etc.	Aluminium, Platinum, Chromium, $CuSO_4$, $MgSO_4$, etc.	Iron, Nickel, Cobalt, Steel, etc.

3.6 DOMAIN THEORY OF FERROMAGNETISM

Weiss put forward a second hypothesis, namely domain hypothesis in order to explain why a virgin sample of ferromagnetic material has spontaneous magnetisation.

Explanation

The entire ferromagnetic volume splits into a large number of small regions called *Domains*. These domains are spontaneously magnetised.

The size of a domain varies from 10^{-6} m to the entire size of the crystal. A domain acts as a single magnetic dipole. Within the domains, all the spin magnetic moments are oriented in one specific direction. The domains are all magnetised in different directions as illustrated in Fig. 3.11 (a).

Within each domain, the magnetic moments (spin) are oriented parallel to the another and energy of each domain is characterised by a definite value and direction of the magnetic field.

In the absence of an external magnetic field, eventhough the magnetic moment vectors of the separate domains are oriented in all probable directions the net magnetic moment exist within the material. All the domains are separated from the other domains by the *Domain wall (or) Block wall.*

Such a piece of ferromagnetic material is said to be unmagnetised.

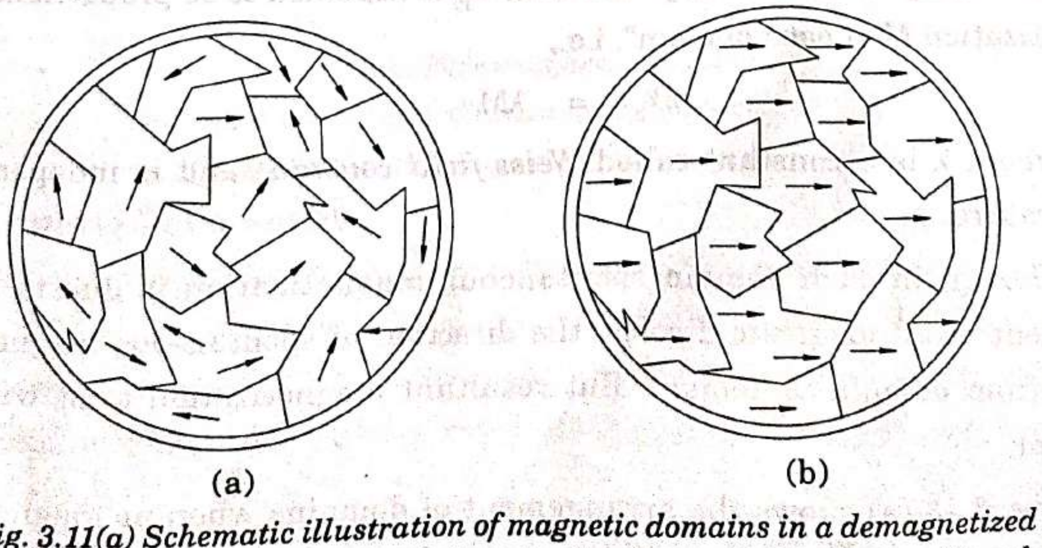


Fig. 3.11(a) Schematic illustration of magnetic domains in a demagnetized ferromagnetic material. In each domain, the magnetic dipoles are aligned but the domains are aligned at random.
(b) Domain configuration in a magnetized body. The magnetic moments of domains are aligned resulting in strong net magnetization.

When the material is subjected to an external magnetic field, the domains rotate and attempt to align their magnetic moments with the field direction instead of the individual atomic dipoles attempting to line up parallel to the field. Fig. 3.11 (a & b) and Fig. 3.12 (a, b & c).

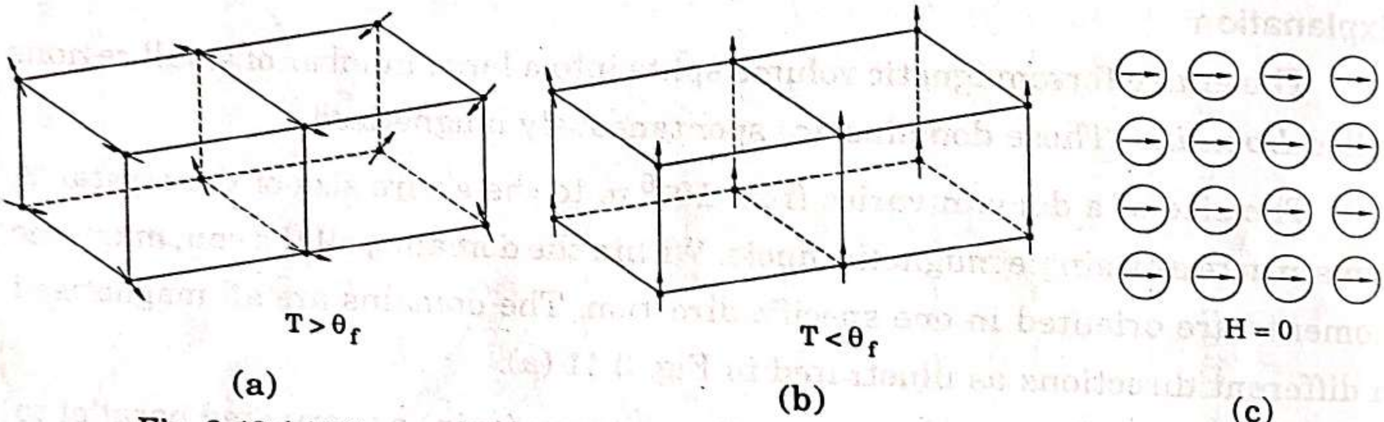


Fig. 3.12 (a) The random orientation of spin moments in a ferromagnetic crystal at temperatures above ferromagnetic Curie temperature θ_f.
(b) The parallel alignment of spins at temperatures below θ_f
(c) Schematic illustration of the mutual alignment of spins in a ferromagnetic material even in the absence of an external magnetic field.

The spontaneous magnetization of each domain is due to the presence of an exchange field B_E which tends to produce a parallel alignment of the atomic dipoles.

According to *Weiss Thoery* "the field B_E is assumed to be proportional to the magnetization M of each domain", i.e.,

$$B_E = \lambda M$$

where λ is a constant called *Weiss-field constant* and is independent of temperature.

Though in each domain spontaneous magnetisation is due to parallel alignment of all magnetic dipoles, the direction of spontaneous magnetization varies from domain to domain. But resultant magnetization exist within the material.

Fig. 3.13 (a) shows the arrangement of domains when no magnetic field is applied.

When an external magnetic field is applied, there are two possible ways of alignment of a random domain.

(i) By the movement of domain walls

Movement of domain walls take place in weak magnetic field. When a small magnetic field is applied, the domains with magnetisation direction becomes parallel or nearly parallel to the field, grow at the expense of others as shown in Fig. 3.13 (b).

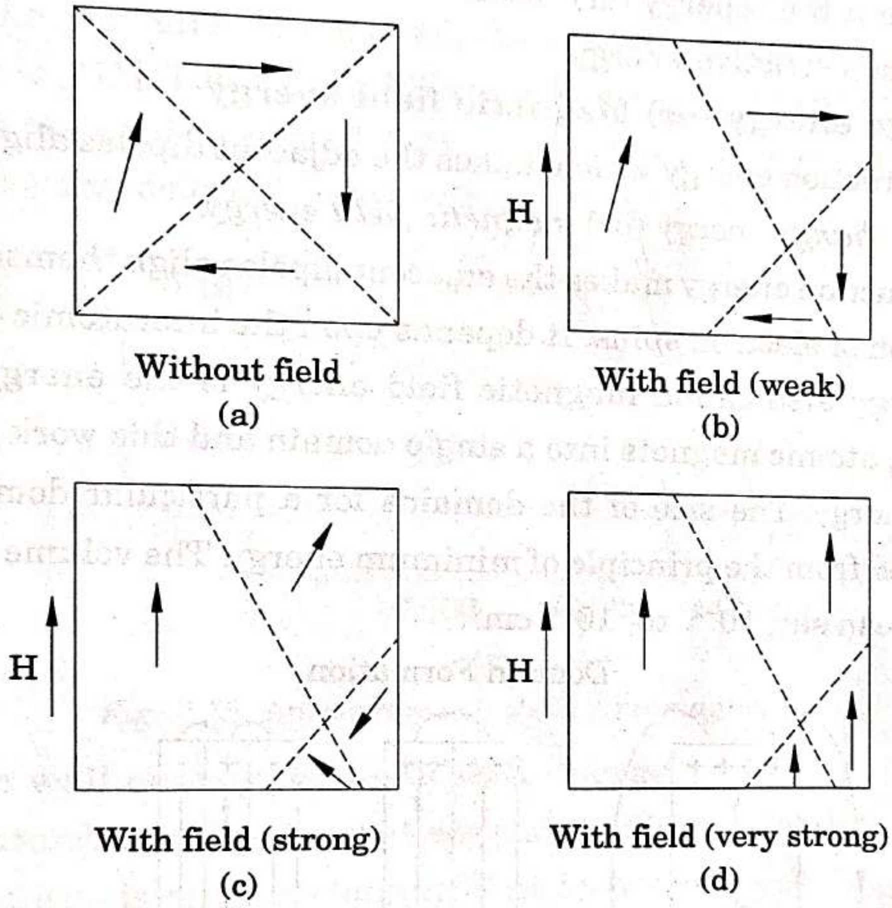


Fig. 3.13 (a) Ferromagnetic domains
(b) Domain magnetization by wall movement
(c) & (d) Domain magnetization by rotation.

(ii) By rotation of domains

Rotation of domain walls occurs during strong magnetic field. As the magnetic field is increased to a larger value (near saturation), further domain growth becomes impossible. Therefore, most favourably oriented and fully grown domains tend to rotate so as to be in complete alignment with the field direction (Fig. 3.13 (c & d)).

3.6.1 Domain Energies and Explanation for Origin of Domains

We can understand the origin of domains from the thermodynamic principle i.e., in equilibrium, the total energy of the system is minimum.

The total internal energy of the domain structure in a ferromagnetic material is made up from the following contributions.

i. Exchange energy (or) Magnetic field energy

ii. Crystalline energy (or) Anisotropy energy.

iii. Domain wall energy (or) Bloch wall energy.

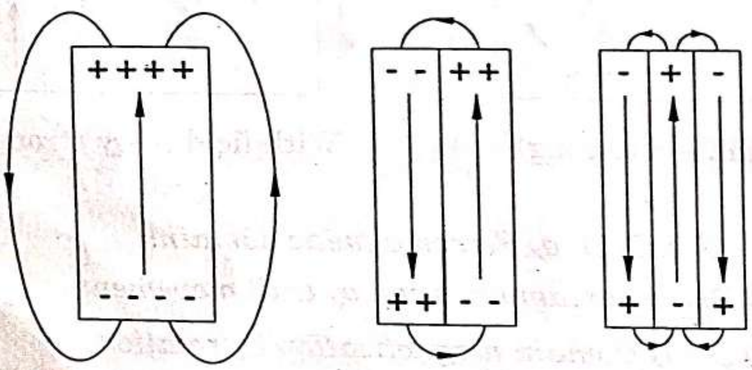
iv. Magnetostrictive energy.

i. Exchange energy (or) Magnetic field energy

"The interaction energy which makes the adjacent dipoles align themselves" is the called *exchange energy* (or) *magnetic field energy*.

The interaction energy makes the adjacent dipoles align themselves. It arises from interaction of electron spins. It depends upon the interatomic distance. This exchange energy also called magnetic field energy is the energy required in assembling the atomic magnets into a single domain and this work done is stored as potential energy. The size of the domains for a particular domain structure may be obtained from the principle of minimum energy. The volume of the domain may very between say, 10^{-2} to 10^{-6} cm^3.

Domain Formation



Total Energy = Magnetostatic Energy + Wall Energy

Fig. 3.14 Exchange energy in ferromagnetism

ii. Anisotropy energy

The excess energy required to magnetize a specimen in particular direction over that required to magnetize it along the easy direction is called the *crystalline anisotropy energy*.

In ferromagnetic materials there are two types of directions of magnetisation namely, (i) easy direction and (ii) hard direction.

In easy direction of magnetisation, weak field can be applied and in hard direction of magnetisation, strong field should be applied.

Crystalline anisotropy energy is energy of magnetization which is the function of crystal orientation. In Fig. 3.15 magnetization curves for iron with the applied field along different crystallographic directions have been drawn. For example, in BCC iron the easy direction is [100], the medium direction is [110], and the hard direction is [111]. The energy difference between hard and easy direction to magnetise the material is about 1.4×10^4 Jm^{-3}. This energy is very important in determining the characteristic domain boundaries.

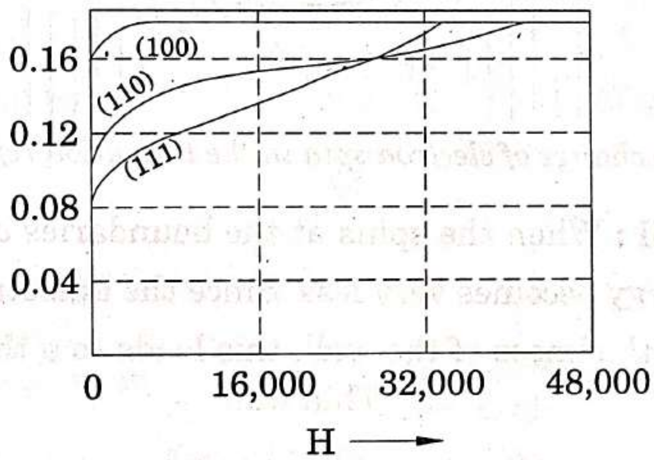


Fig. 3.15 Anisotropy energy in ferromagnetism

iii. Domain wall energy or Bloch wall energy

A thin boundary or region that separates adjacent domains magnetized in different directions is called *domain wall* or *bloch wall.*

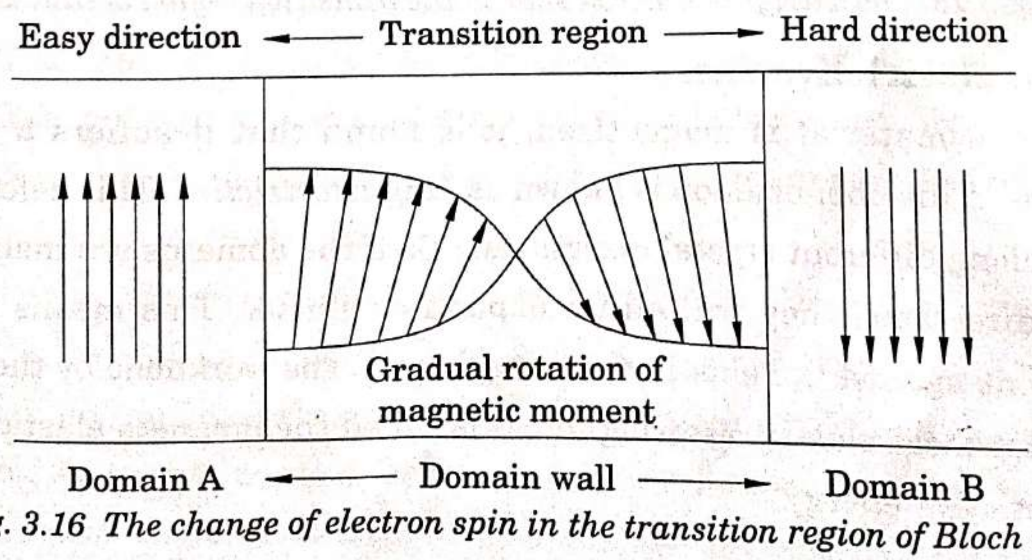


Fig. 3.16 The change of electron spin in the transition region of Bloch wall

The size of the bloch walls are about 200 to 300 lattice constant thickness. In going from one domain to another domain, the electron spin changes gradually as shown in Fig. 3.16.

The energy of domain wall is due to both exchange energy and anisotropic energy.

Based on the spin alignments, two types of bloch walls may arise, namely

(i) Thick Wall : When the spins at the boundary are misaligned and if the direction of the spin *changes gradually* as shown Fig. 3.17, it leads to a thick bloch wall. Here the misalignment of spins are associated with exchange energy.

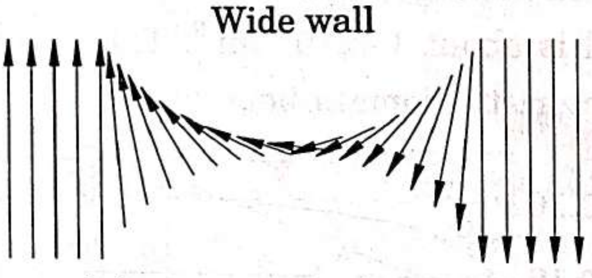


Fig. 3.17 The change of electron spin in the transition region of thick wall

(ii) Thin Wall : When the spins at the boundaries *changes abruptly*, then the anisotropic energy becomes very less. Since the anisotropic energy is directly proportional to the thickness of the wall, this leads to a thin Bloch wall.

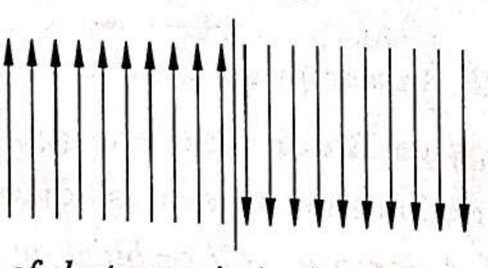


Fig. 3.18 The change of electron spin in the transition region of thin wall

iv. Magnetostrictive energy

When a material is magnetized, it is found that it suffers a change in dimensions. This phenomenon is known as *Magnetostrictive*. This deformation is different along different crystal directions. So if the domains are magnetized in different directions, they will either expand or shrink. This means that work must be done against the elastic restoring forces. The workdone by the magnetic field against these elastic restoring forces is called the magneto-elastic energy or magnetostrictive energy.

3.7 HYSTERESIS

The word hysteresis literally means lagging behind. "When a ferromagnetic material is taken through a cycle of magnetisation, the variation of B (magnetic induction) with respect to H (applied field) can be represented by a closed loop (or) curve (hysteresis loop or curve)" is called *hysteresis*.

A graph is drawn plotting magnetic field strength 'H' along X-axis and magnetic induction 'B' along Y-axis as shown in Fig. 3.19.

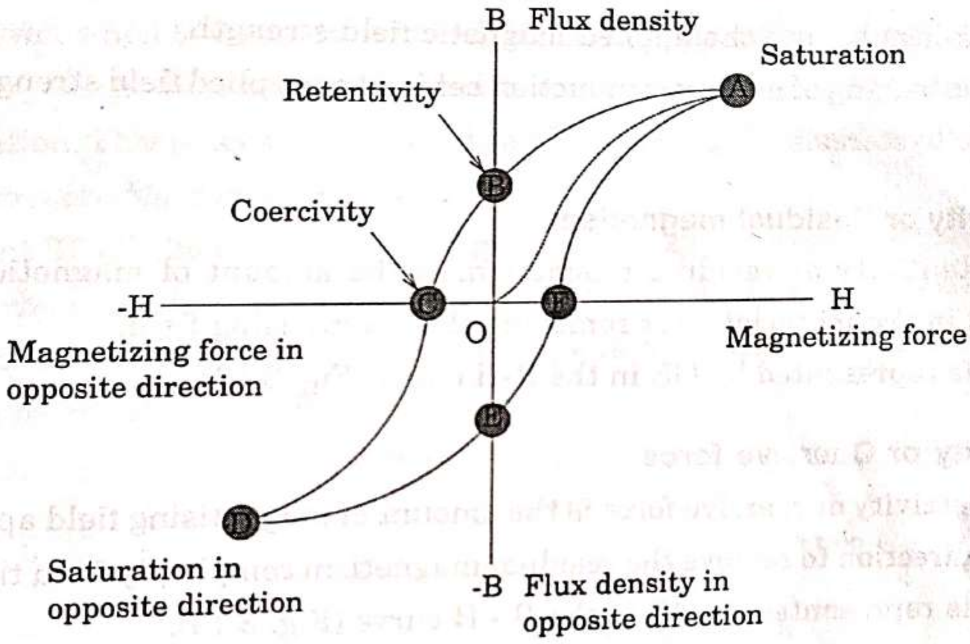


Fig. 3.19 Hysteresis loop

1. The magnetic induction (B) increases along the curve OA with the magnetic field (H). Beyond the point A, even if the magnetic field is increased, the magnetic induction does not increase and it remains constant. At this point, the specimen is saturated with magnetisation.
2. The value of magnetic field is decreased, but the magnetic induction does not decrease at the rate at which it is increased. When H = 0, B ≠ 0, the magnetic induction has a definite value represented by OB and it is known as *Retentivity*.
3. The applied magnetic field H is reversed and increased gradually till the point C is reached. The magnetic induction B becomes zero at the point C and negative magnetic field strength applied to remove residual magentism is denoted by OC and it is known as *Coercivity*.
4. Further increase of magnetic field H, the magnetic induction increases along CD in the reverse direction as shown in the graph. If the magnetic field is varied backwards, the magnetic induction follows a curve DEFA.

This will complete one cycle of magnetisation. The loop ABCEDFA is called *hysteresis loop.*

From the above fact, it is clear that the magnetic induction B will not become zero, when the magnetic field strength H is zero. It shows that the magnetic induction lags behind the applied magnetic field strength.

This lagging of magnetic induction behind the applied field strength is called magnetic hysteresis.

Retentivity or Residual magnetism

Retentivity or residual magnetism is the amount of magnetic induction retained in the material after removing the magnetising field.

It is represented by OB in the B-H curve (Fig. 3.19).

Coercivity or Coercive force

Coercivity or coercive force is the amount of magnetising field applied in the reverse direction to remove the residual magnetism completely from the material.

It is represented by OC in the B - H curve (Fig. 3.19).

Hysteresis loss

When the specimen is taken through a cycle of magnetization, there is a loss of energy in the form of heat. This loss of energy is known as hysteresis loss.

The area of the loop represents energy loss per cycle per unit volume of the specimen.

3.7.1 Explanation of Hysteresis on the basis of Domain theory

It is found that when a ferromagnetic material is subjected to an external field, there is an increase in the value of the resultant magnetic moment of the specimen.

This is due to

1. Motion of domain walls
2. Rotation of domain walls

When a small external field is applied, the domain walls are displaced slightly in the easy direction of magnetisation. This gives rise to small magnetisation corresponding to the initial portion of the hysteresis curve (OA) as shown in Fig. 3.20.

When the applied field is removed then the domains return to its original state and is known as *reversible domains.*

If the field is increased, large number of domains contribute to the magnetisation and thus the magnetization increases rapidly with H.

Now, even when the field is removed, because of the displacement of domain wall to a very large distance the domain boundaries do not come back to their original position. This process is indicated as AB in the Fig. 3.20 and these domains are called *irreversible domains.*

At point 'B' all the domains got magnetised along the easy direction.

Now, when the field is further increased, the domains start rotating along the field direction and the anisotropic energy is stored in the hard direction represented by BC in Fig. 3.20.

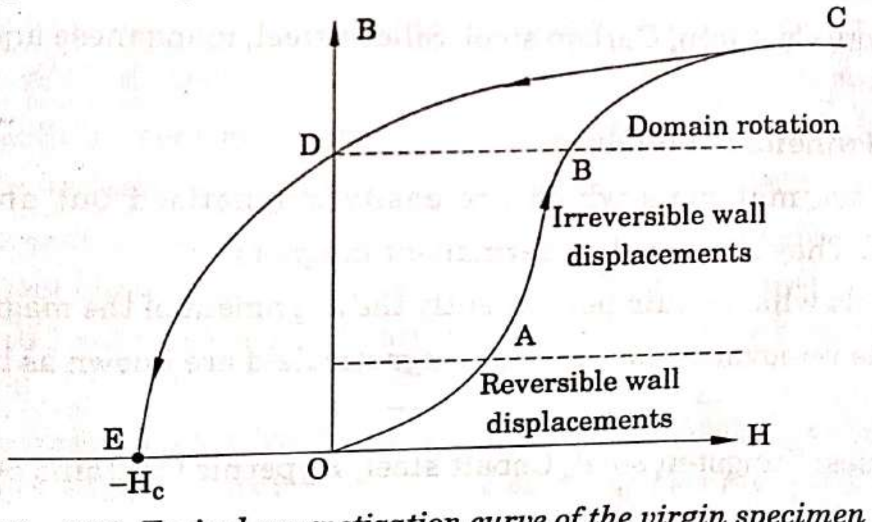


Fig. 3.20 Typical magnetization curve of the virgin specimen

Thus, the specimen is said to have attained the maximum magnetisation. At this position, even after the removal of external field the material posses maximum magnetisation called *residual magnetism (or) retentivity* represented by OD in Fig. 3.20.

On the removal of the external field, the specimen will try to attain the original configuration by the movement of Bloch wall. But this movement is stopped due to the presence of impurities, lattice imperfections etc. Therefore to overcome this, a large amount of reverse magnetic field is applied to the specimen. The amount of energy spent to reduce the magnetisation to zero is called *coercivity* represented by OE in the Fig. 3.20.

3.8 CLASSIFICATION OF MAGNETIC MATERIALS

Based on the area of the hysteresis loop, the magnetic materials are classified into soft and hard magnetic materials.

Generally the magnetic materials are classified into two types. They are

i. Soft Magnetic materials

ii. Hard Magnetic materials

3.8.1 Soft Magnetic materials

These are materials which are easily magnetised and demagnetised. They are also called as temperory magnets. Magnetic materials which do not retain the alignment of magnetic domains after the removal of the external magnetic field are known as soft magnetic materials.

Examples:

Pure iron, Cast iron, Carbon steel, Silicon steel, manganese and nickel steel, soft ferrites.

3.8.2 Hard Magnetic materials

These are materials which are easily magnetised but are difficult to demagnetise. They are called as permanent magnets.

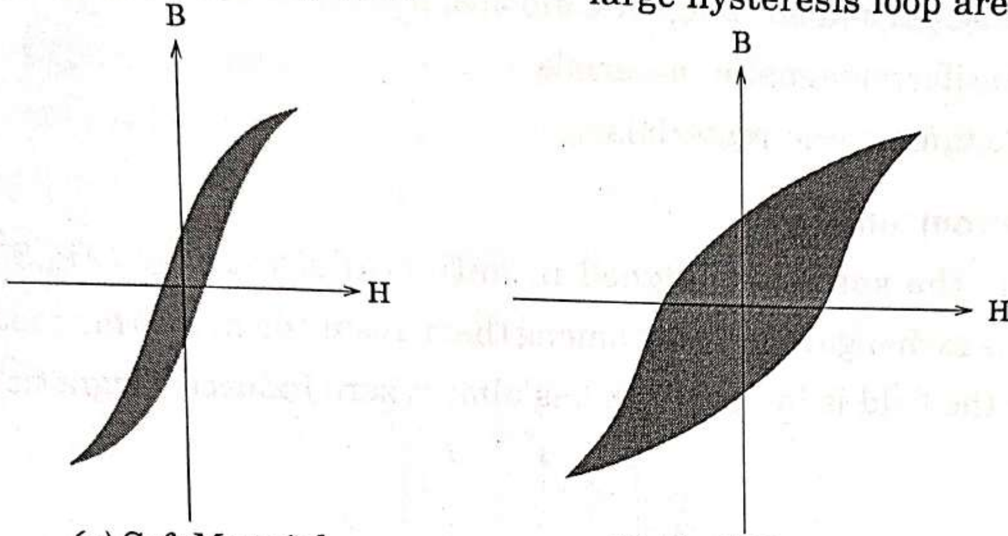
Materials which retain permanently the alignment of the magnetic domains even after the removal of the external magnetic field are known as hard magnetic materials.

Examples: Tungsten steel, Cobalt steel, Hypernic (contains 50% nickel and 50% iron).

3.8.3 Difference between Soft and Hard magnetic materials

Sl. No.	Soft Magnetic materials (Temparary magnet)	Hard Magnetic materials (Permanent magnet)
1.	Magnetic materials which can be easily magnetised and demagnetised.	Magnetic materials which can be easily magnetised and difficult to demagnetise.
2.	They have high permeability and Susceptibility.	They have low permeability and Susceptibility.
3.	Magnetic energy stored is not high.	Magnetic energy stored is high.

4.	Low hysteresis losses due to small hysteresis loop area.	Large hysteresis losses due to large hysteresis loop area.



(a) Soft Material (b) Hard Material

Fig. 3.21 Hard and soft magnetic materials

5.	Hysteresis loop is very narrow.	Hysteresis loop is very broad.
6.	Coercivity and retentivity are small.	Coercivity and retentivity are large.
7.	The eddy current loss is small due to its higher resistivity.	The eddy current loss is more due to its smaller resistivity.
8.	Movement of domain wall is easy and hence even for a small applied field large magnetization occurs.	Movement of domain wall is not easy due to the presence of impurities and hence large field is required.
9.	These materials are free from irregularities like strain or impurities.	These materials have large amount of impurities and lattice defects.
10.	These are produced by heating them into sufficient temperature & then allowed to cool slowly connecting process.	These are produced by heating them into sufficient temperature & then plunging it suddenly into cold oil.
11.	Examples: Iron silicon alloy, Nickel iron alloy, silicon steels, ferrites. Applications	Examples: Tungsten steel, Cobalt steel, Alini, Alnico, Cunife. Applications
12.	They are used in electric motor, generators, transformers, relays, telephone receivers, radar and Sonar equipments.	They are used in loud speakers and electrical measuring instruments.

3.9 CLASSIFICATION OF FERROMAGNETIC MATERIALS

Based on permanent magnetic dipoles, materials are further classified into

i. Antiferromagnetic materials

ii. Ferrimagnetic materials.

3.9.1 Antiferromagnetism

In this the spins are aligned in antiparallel manner (Fig.3.22) due to unfavourable exchange interaction among them, resulting in zero magnetic moment. Even when the field is increased, it has almost zero induced magnetic moment.

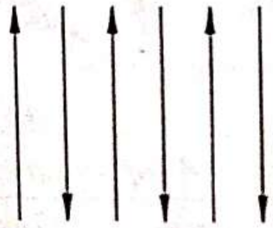


Fig. 3.22 Spin alignment in antiferromagnetic materials

Antiferromagnetic materials are crystalline materials which exhibit a small positive susceptibility of the order of 10^{-3} to 10^{-5}. The variation of susceptibility with temperature follows a peculiar pattern in these materials. The susceptibility increases with increasing temperature and reaches a maximum at a certain temperature called *Neel temperature*, T_N (Fig. 3.23(a)).

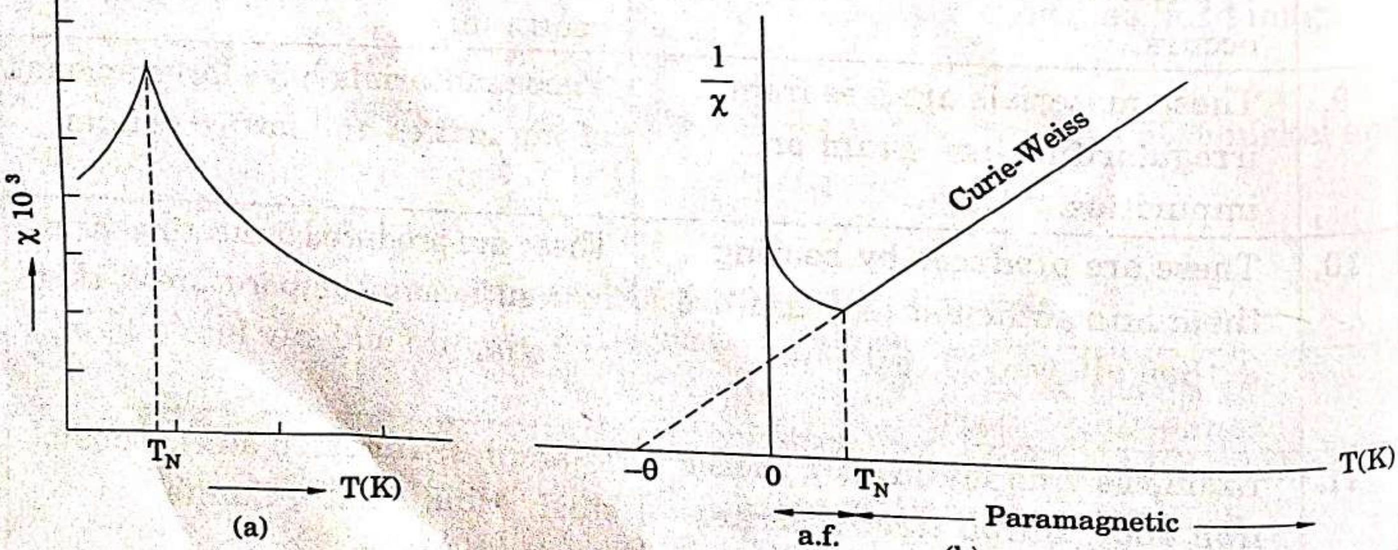


Fig. 3.23 (a) Variation of susceptibility of an antiferromagnetic crystal as a function of temperature (T)
(b) The reciprocal of susceptibility of an antiferromagnetic crystal versus temperature.

With further increase in temperature, the material goes into paramagnetic state. The material is antiferromagnetic below T_N. The transition temperature T_N lies below the room temperature for most of the materials.

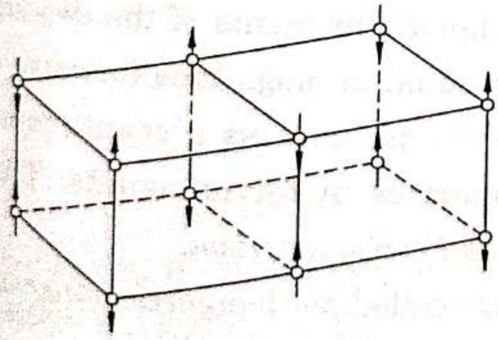
In the paramagnetic state, the variation of inverse susceptibility $(1/\chi)$ with temperature is linear, as shown in Fig. 3.23 (b).

The extrapolation of the paramagnetic line in Fig. 3.23 (b) to $1/\chi = 0$ yields a negative θ. The variation of susceptibility with temperature obeys *Curie-Weiss Law.* Therefore Curie - Weiss Law is modified as.

$$\chi_{a.f} = \frac{C}{T-(-\theta)} = \frac{C}{T+(\theta)} \quad \text{when } T > T_N$$

Where θ is called Paramagnetic Curie temperature and C is Curie constant.

The elements manganese and chromium exhibit antiferromagnetism at room temperature. Most of the antiferromagnetic materials are ionic compounds. MnO, MnS, $FeCl_2$, FeO, Cr_2O_3, NiCr are some of the compounds which exhibit antiferromagnetism. Salts of transition elements do exhibit antiferromagnetism.



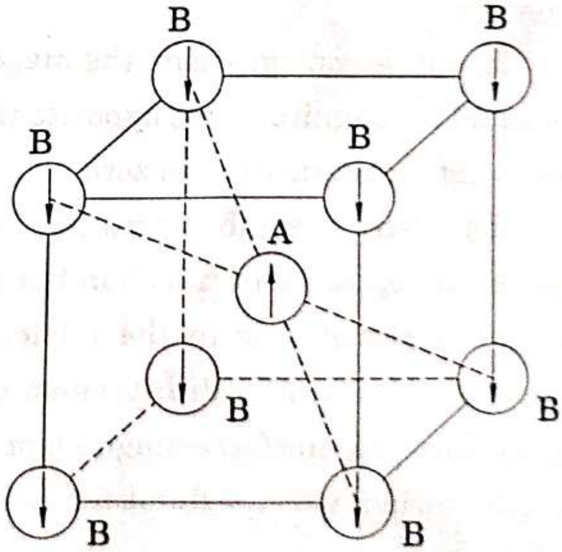


Fig. 3.24 (a) Alignment of spin moments in an antiferromagnetic simple cubic crystal at temperature below Neel temperature
(b) Alignment of spin moments in an antiferromagnetic body centred cubic crystal. The crystal may be represented with two sub lattices A and B, having antiparallel spin moment orientations.

The antiferromagnetic character is explained to be a consequence of antiparallel alignment of neighbouring magnetic moments in the crystal as shown in Fig. 3.24.

As a result, the magnetic moments cancel each others effect.

Properties of antiferromagnetic materials

i. Electron spin of neighbouring atoms are aligned antiparallel. Therefore net magnetisation is zero.

ii. Antiferromagnetic susceptibility depends greatly on temperature.

iii. The susceptibility of antiferromagnetic material is small and positive. It is given by

$$\chi = \frac{C}{T+\theta}$$ When $T > T_N$

Where T_N - Neel temperature

$$\chi \propto T$$ When $T < T_N$

iv. Initially susceptibility increases slightly with temperature and beyond Neel temperature the susceptibility decreases with the temperature.

3.9.2 Ferrimagnetic Materials (or) Ferrites

Ferrites are another group of soft magnetic materials which are ferrimagnetic in nature.

In antiferromagnetism, the magnetic moments of sub lattices in crystal cell are equal in magnitude but opposite in direction, so they cancel each other giving rise to net magnetization as zero.

But there are substances in which the magnetic moments of the two sub lattices are opposite in direction but not exactly equal in magnitude (because of the two types of ions in the lattices). Such crystals possess a spontaneous magnetization and exhibit most of the properties of ferromagnets. This uncompensated antiferro-magnetism is known as *Ferrimagnetism.*

Materials which exhibit ferrimagnetism are called *ferrimagnetic materials or ferrites.*

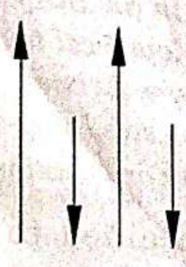


Fig. 3.25

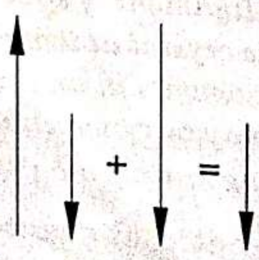


Fig. 3.26

Structure of ferrites

Ferrites are the magnetic compounds consisting of two or more different kinds of atoms. Generally ferrites are expressed as $X^{2+} Fe_2^{3+} O_4$ where X^{2+} stands for suitable divalent metals ions such as Mg^{2+}, Zn^{2+}, Fe^{2+}, Mn^{2+}, Ni^{2+} etc.

Normally, there are two types of structures present in the ferrites

i. Regular spinal

ii. Inverse spinal

Regular spinal

In the regular spinal type, each metal atom (divalent) is surrounded by four O^{2-} ions in a tetragonal fashion.

For example in $Mg^{2+} Fe_2^{3+} O_4^{2-}$, the structure of Mg^{2+} is given in the Fig. 3.28 and it is called 'A' site. Totally in an unit cell, there will be 8 tetrahedral (8A) sites.

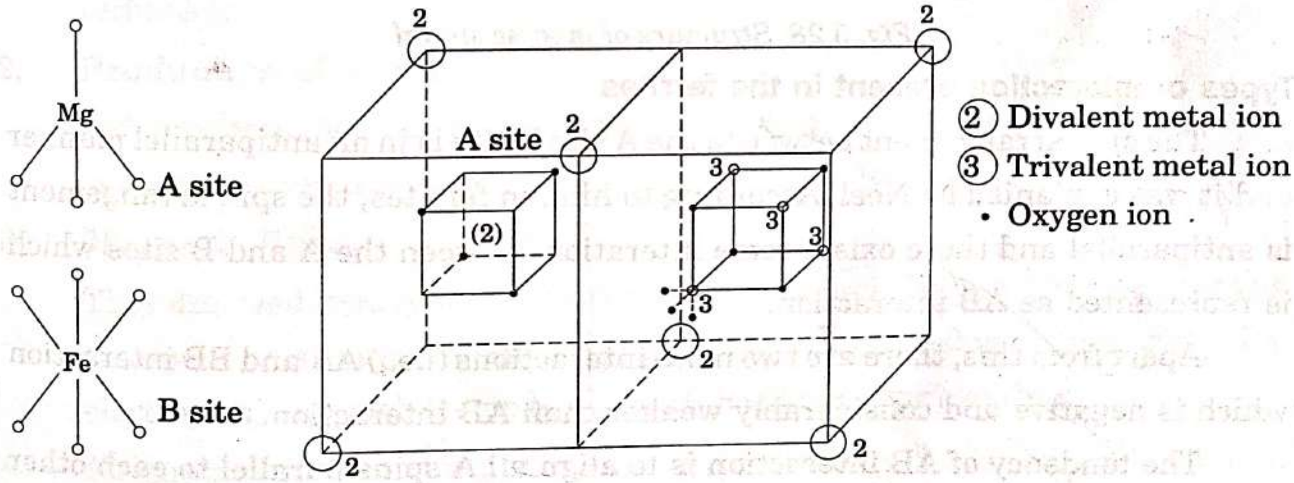


Fig. 3.27 Structure of ferrites (Regular Spinal)

Each Fe^{3+} (trivalent) is surrounded by '6' O^{2-} ions and forms an octahedral fashion as shown in Fig. 3.27. Totally there will be 16 such octahedral sites in the unit cell. This is indicated by 'B' site.

Thus in a regular spinal, each divalent metal ion (Mg^{2+}) exists in a tetrahedral form (A site) and each trivalent metal ion (Fe^{3+}) exists in a octahedral form (B site). Hence, the sites A and B combine together to form a regular spinal ferrite structure as shown in Fig. 3.27.

Inverse spinal

In this type, we consider the arrangement of dipoles of a single ferrous ferrite molecule $Fe^{3+}[Fe^{2+} Fe^{3+}]O_4^{2-}$, Fe^{3+} ions (trivalent) occupies all A sites (tetrahedral) and half of the B sites (octahedral) also.

Thus the left out B sites will be occupied by the divalent (Fe^{2+}). The inverse spinel structure is shown in the Fig. 3.28.

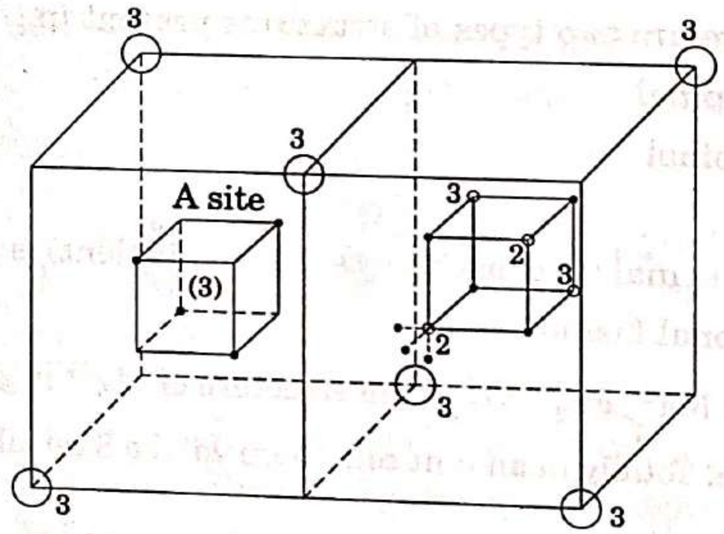


Fig. 3.28 Structure of inverse spinal

Types of interaction present in the ferrites

The spin arrangement betweeen the A site B site is in an antiparallel manner and it was explanied by Neel. According to him, in ferrites, the spin arrangement is antiparallel and there exists some interation between the A and B sites which is represented as AB interaction.

Apart from this, there are two more interactions (i.e.,) AA and BB interaction which is negative and considerably weaker than AB interaction.

The tendency of AB interaction is to align all A spins parallel to each other and antiparallel to all B spins, but the tendency of AA and BB interaction is to spoil the parallel arrangement of AB spins respectively.

Since AB is very strong as compared with AA and BB, the effect of AB interaction dominates and give rise to antiparallel spin arrangement.

Properties of ferrimagnetic materials

i. Ferrimagnetic materials posses net magnetic moment.

ii. Above Curie temperature, it becomes paramagnetic while it behaves as ferrimagnetic material below Curie temperature.

iii. The susceptibility of ferrimagnetic material is very large and positive. It is temperature dependent and is given by

$$\chi = \frac{C}{T \pm \theta} \qquad \text{for } T > T_N$$

iv. Beyond Neel temperature, χ decreases

v. Spin alignment is antiparallel of different magnitudes (Fig. 3.25).

vi. Mechanically, it has pure ion character.

vii. They have high permeability and high resistivity.

viii. They have low eddy current losses and low hysteresis.

3.10 APPLICATIONS OF FERRITES

1. **Manufacture of permanent magnet**

   Hard magnetic ferrites are used in the manufacturing of permanent magnets which possess high electrical resistance.

   Such magnets find use in certain applications involving super-high frequency technology.

2. **Production of cores**

   Soft magnetic ferrites are used in the production of cores for inductor coils used in telecommunication and low-power transformers.

3. **Magnetic films**

   They are used in magnetic films in which demagnetization process occurs at the speed exceeding million times/second. This technology is important for electronics, automobiles and computer hardware engineering.

4. **Magnetic discs and tapes**

   They are used in magnetic discs or tapes in which the concept of magnetic bubbles is used. The concept of magnetic bubble plays an important role in information storage devices such as magnetic discs and tapes. Magnetic bubbles serve as memory elements in such devices.

5. They are used to produce ultrasonic waves by magnetostriction principle.

6. Ferrite rods are used in radio receiver to increase the sensitivity.

7. Since the ferrites has low hysteresis loss and eddy current loss, they are used in two port devices such as gyrator, circulator and isolator.

   Gyrator : It transmits the power freely in both directions with a phase shift of radians.

In video cassette, the recording is more complicated. It involves the moving of the head helically, which increases the speed of the tape and hence the induced voltage.

3.11.2 Magnetic storage devices

In a magnetic storage, chromium dioxide, barium ferrite and metal evaporated thin film materials are used as storage media. When we apply a magnetic field in a magnetic materials which have high permeability and susceptibility, the magnetic moments are induced. Through these induced magnetic moment can record the information.

The memory units are mainly classified into two categories.

i. Main Memory (Primary) (or) Internal Memory.

ii. Auxillary Memory (Secondary) (or) External Memory.

(i) Main memory

The memory unit of the Central Processing Unit (CPU) is called as main memory. We can compare a black board to main memory. Here we can write so many datas on the memories and finally can be erased, if we need to erase it.

Examples : RAM, ROM, EPROM, etc.,

(ii) Auxillary memory

Since the storage capacity of the primary memories are not sufficient, Secondary (or) auxillary memory units are developed to store the large volume of data, separately and hence called as extra (or) additional (or) external memory.

This type of memory is also referred to as back-up storages because, it is used to store large volume of data on a permanent basis.

The datas in auxillary memory can also be transferred to primary memory (i.e.,) to computer partially, when required for processing. This can be compared to a book, from which we can access (or) take copies as we need.

Examples :

i. Magnetic tapes (Cassettes).

ii. Magnetic disk (Floppy and Hard disk).

iii. Ferric core memories.

iv. Magnetic Bubble memories.

(5) The information stored in the magnetic medium can be easily destroyed. This can be done by small magnetic field. Therefore, electrical or magnetic field from outside in close contact with the magnetic field from outside in close contact with the magnetic medium will erase or corrupt the data.

3.11.4 Magnetic disks

These disks are direct access storage devices. These disks are magnetically coated. There are two types of disks viz.,

i. Hard disk

ii. Floppy disk

i. Hard Disk

Construction

The hard disk is made of hard aluminium platters. The platter surface is carefully machined until it is flat (or) plane. The platter surface is coated with magnetic material (magnetic oxides). The platter is build into a box.

Similar such disks are mounted on a vertical shaft, forming a disk pack and it is shown in Fig. 3.32.

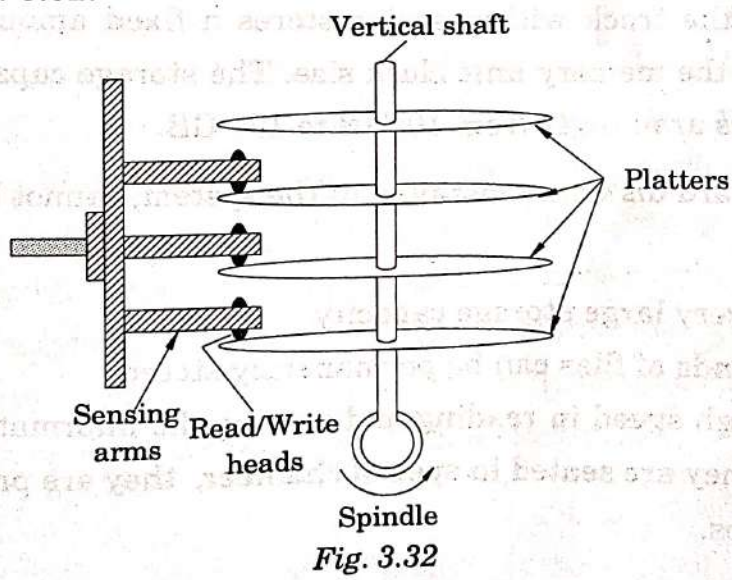


Fig. 3.32

This disk pack is placed in a drive mechanism called Hard disk drive. The drive mechanism drives the disk pack with the spindle. The data is written (or) read by the Read/Write heads in the horizontal sensing arms by moving in and out between the platters with the precaution that the Read/Write head doesn't touches the surface instead, it fly over the disk surface by the fraction of a mm.

Working

During the operation of memory, the disks are rotated at a uniform speed by a disk drive unit. The rotational speed of the disk vary. But typical speeds are in the order of 3600 rpm. Each recording surface consists of at least one read and write head. Read and write heads are used to store the information on the surface of the rotating disks. These heads are mounted on access arms. Using this arms, a particular set of track for reading/writing can be selected.

The total time taken to select and read a data or select a track and write a data is called access time. The time required to hold a head on the selected track is called the seek time, which is generally in several milliseconds. The time required for the desired data to reach the magnetic head is latency or rotational delay, which is maximum of 20 milliseconds. Hence total access time for a disk is the seek time plus the latency. The rate at which bits are transferred once the reading or writing begins is called the transfer rate twenty to thirty millions bits per second is a good transfer rate.

Similar to the floppy disk, the reading surface is divided into sectors. As a result a part of the track within sector stores a fixed amount of information corresponding to the memory unit block size. The storage capacity of hard disks used in computers are ranges from 10 MB to 160 GB.

Note : The hard disk once installed in the system, cannot be removed easily.

Advantages

i. It has very large storage capacity.

ii. Thousands of files can be permanently stored.

iii. Very high speed in reading and writing the informations.

iv. Since they are seated in special chamber, they are prevented from dust particles.

Disadvantages

i. It is very costly.

ii. If data is once corrupted, there is a heavy loss of data.

ii. Floppy disk

The hard disks are suitable only for large and medium sized computers and

SOLVED PROBLEMS

1. A paramagnetic material has a magnetic field intensity of 10^4 A m^{-1}. If the susceptibility of the material at room temperature is 3.7×10^{-3}. Calculate the magnetization and flux density in the material.

Given

$H = 10^4$ A m^{-1}, $\chi = 3.7 \times 10^{-3}$, $I = ?$ $B = ?$

Solution

(i)

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

$$I = \chi H$$

$$= 3.7 \times 10^{-3} \times 10^{4}$$

$$= 3.7 \times 10$$

$$I = 37 \text{ A m}^{-1}$$

(ii)

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

$$= 4\pi \times 10^{-7} \times (37 + 10^4)$$

$$= 126179.4 \times 10^{-7}$$

$$B = 0.0126 \text{ Wb m}^{-2}$$

2. A magnetic material has a magnetization of 2300 A m^{-1} and produces a flux density of 0.00314 Wb m^{-2}. Calculate the magnetizing force and the relative permeability of the material.

Given

$I = 2300$ A m^{-1}, $B = 0.00314$ Wb m^{-2}, $H = ?$, $\mu_r = ?$

Solution

(i)

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

$$H = \frac{B}{\mu_0} - I$$

$$= \frac{0.00314}{4\pi \times 10^{-7}} - 2300$$

$$H = 198.7326 \text{ A m}^{-1}$$

(ii)

$$\chi = \frac{I}{H} = (\mu_r - 1)$$

$$\mu_r = \frac{I}{H} + 1$$

$$= \frac{2300}{198.7326} + 1$$

$$\mu_r = 12.573$$

3. A paramagnetic material has BCC structure with a cubic edge of 2.5 Å. If the saturation value of magnetization is 1.8×10^6 Am^{-1}, Calculate the magnetization contributed peratom in Bohr magnetons.

Given

$a = 2.5 \times 10^{-10}$ m, $I = 1.8 \times 10^6$ A m^{-1}, $M_T = ?$

Solution :

The number of atoms present per unit volume

$$N = \frac{\text{Number of atoms present in an unit cell}}{\text{Volume of the unit cell}}$$

$$= \frac{2}{(2.5 \times 10^{-10})^3}$$

$$N = 1.28 \times 10^{29} \text{ m}^{-3}$$

$$\text{The magnetization produced per atom} = \frac{\text{Total magnetisation}}{\text{No. of atoms per unit volume}}$$

$$= \frac{I}{N}$$

$$= \frac{1.8 \times 10^6}{1.28 \times 10^{29}}$$

$$I_T = 1.40625 \times 10^{-23} \text{ A m}^{-2}$$

$$\mu_B = \frac{eh}{4\pi m}$$

$$= \frac{1.6 \times 10^{-19} \times 6.625 \times 10^{-34}}{4 \times 3.14 \times 9.1 \times 10^{-31}}$$

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

∴ Magnetisation produced per atom in Bohr magneton

$$= \frac{1.40625 \times 10^{-23}}{9.27 \times 10^{-24}}$$

$$= 1.516 \text{ Bohr magneton}$$

4. **The saturation magnetic induction of Nickel is 0.65 Wb m^{-2}. If the density of Nickel is 8906 Kg m^{-3} and its atomic weight is 58.7. Calculate the magnetic moment of the Nickel atom in Bohr magneton.**

Given

B_S = 0.65 Wb m^{-2}, ρ = 8906 Kg m^{-3}, Atomic Weight = 58.7, μ_m = ?

Solution

$$N = \frac{\rho \times \text{Avogadro number}}{\text{Atomic weight}}$$

$$= \frac{8906 \times 6.023 \times 10^{26}}{58.7}$$

$$N = 9.14 \times 10^{28} \text{ atoms / m}^{-3}$$

When χ is very large, Saturation magnetization

$$B_S = N \mu_0 \mu_m$$

$$\mu_m = \frac{B_s}{N\mu_0}$$

$$= \frac{0.65}{9.14 \times 10^{28} \times 4 \times 3.14 \times 10^{-7}}$$

$$\mu_m = 5.66 \times 10^{-24} \text{ A m}^2$$

Magnetic moment per Bohr magneton

$$\therefore \mu_m = \frac{5.66 \times 10^{-24}}{9.29 \times 10^{-24}} \text{ Bohr magneton}$$

$$\mu_m = 0.61\ \mu_B$$

5. **In a magnetic material the field strength is found to be 10^{6} Am^{-1}. If the magnetic susceptibility of the material is 0.5 x 10^{-5}. Calculate the intensity of magnetization and flux density in the material.**

Given

H = 10^{6} A m^{-1}, χ = 0.5 x 10^{-5}, B = ? I = ?

Solution

(i)

$$I = \chi H$$

$$= 0.5 \times 10^{6} \times 10^{-5}$$

$$I = 5 \text{ A m}^{-1}$$

(ii)

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

$$= 4 \times 3.14 \times 10^{-7} (5 + 10^{6})$$

$$B = 1.257 \text{ Wbm}^{-2}$$

6. **The critical temperature of Niobium is 9.15 K. At 0K the critical field is 0.196 T. Calculate the critical field at 5 K.**

Given

$T_c = 9.15$ K, $T = 5$ K, $H_0 = 0.196$ T, $H_c = ?$

Solution

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

$$= 0.196\left[1-\frac{5^2}{9.15^2}\right]$$

$$= 0.196 \times 0.7014$$

$$H_c = 0.1374 \text{ Tesla}$$

7. **Calculate the critical current through a long thin superconducting wire of radius 0.5 mm. The critical magnetic field is 42.75 x 10^3 A/m.**

Given

$r = 0.5 \times 10^{-3}$ m, $H_c = 42.75 \times 10^3$ A/m, $I_c = ?$

Solution

$$I_c = 2\pi r H_c$$

$$= 2 \times 3.14 \times 0.5 \times 10^{-3} \times 42.75 \times 10^3$$

$$I_c = 134.25 \text{ Ampere}$$

8. **Calculate the critical current for a superconducting wire of lead having a diameter of 1 mm at 4.2 K. Critical temperature for lead is 7.18 K and $H_c(0) = 6.5 \times 10^4$ A/m.**

Given

$r=0.5 \times 10^{-3}$ m, $T = 4.2$ K, $T_c = 7.18$ K, $H_0 = 6.5 \times 10^4$ A/m, $I_c = ?$, $H_c = ?$

Solution

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

$$= 6.5 \times 10^4\left(1-\frac{4.2^2}{7.18^2}\right)$$

$$= 6.5 \times 10^4 (1 - 0.3421)$$

EXERCISE PROBLEMS

1. The magnetic field intensity of a ferric oxide piece is 10^6 A m^{-1}. If the suspectibility of the material at room temperature is 10.5×10^{-3}, calculate the flux density and magnetization of the material.

   (Ans : B = 1.259 T and M = 1500 A m^{-1})

2. The saturation value of magnetization of iron is 1.76×10^6 amp/m. Iron has body centered cubic structure with elementary cube edge of 2.86 AU. Calculate the average number of Bohr magneton contributed to magnetisation per atom. **(Ans : 2.22 Bohr magneton/atom)**

3. A superconducting tin has a critical temperature of 3.7 K at zero magnetic field and a critical field of 0.0306 Tesla at 0K. Find the critical field at 2 K.

   (Ans : H_C = 0.02166 Tesla.)

4. The critical temperature for a metal with isotopic mass 199.5 is 4.185 K. Calculate the isotopic mass if the critical temperature falls to 4.133 K.

   (Ans : M_2 = 204.5)

5. Find the critical current which can pass through a long thin superconducting wire of aluminium of diameter 2 mm. The critical magnetic field for aluminium is 7.9×10^3 A m^{-1} **(Ans : I_C = 49.637 A)**

PART - A QUESTIONS & ANSWERS

1. **What is meant by magnetic materials? Give examples ?**

   Magnetic materials are the materials which can be easily magnetised by keeping it in an external magnetic field.

   Examples : Iron, Ferrites, Carbon steel etc.

2. **Define Magnetic Flux [ϕ]**

   The total number of number magnetic lines of force passing through a surface is known as magnetic flux. **Unit :** Weber.

3. **Define magnetic induction (B) or magnetic flux density**

   It is the number of magnetic lines of force passing perpendicular through unit area of cross section. **Unit :** Weber / m^2 or Tesla

4. **Define Intensity of magnetic field or Magnetic field strength or Magnetising field intensity (H).**

It is the force experienced by an unit north pole placed at the given point in a magnetic field. H = A / m, **Unit :** Ampere / metre or N / Wb

5. **Define intensity of magnetisation (I)**

Magnetisation is the process of converting a non – magnetic material into a magnetic material. It is defined as the magnetic moment per unit volume. $I = m / V$ **Unit :** Weber / m^2.

6. **Define magnetic susceptibility (χ)**

It is defined as the ratio of intensity of magnetization produced to apply magnetic field intensity. $\chi = I / H$. The sign and magnitude of χ are used to determine the nature of the magnetic materials.

7. **Define magnetic permeability (μ)**

It is the ratio of the magnetic flux density (B) to the applied magnetic field intensity (H). $\mu = B / H$ **Unit :** Henry / m.

8. **Define relative permeability (μ_r)**

It is defined as the ratio of permeability of the medium (μ) to the permeability of the free space. $\mu_r = \mu / \mu_o$.

9. **Define Bohr magneton (μ_B)** **(AU., Jan 2005)**

The orbital magnetic moment and the spin magnetic moment of an electron in an atom can be expressed in terms of atomic unit of magnetic moment called Bohr magneton. One Bohr magneton, $\mu_B = 9.27 \times 10^{-24}$ A m^2.

10. **How the magnetic materials are classified?**

The magnetic materials are classified into two categories

1. Without permanent magnetic moment.

   Ex: i) Diamagnetic materials.

2. With permanent magnetic moment.

   Ex: i) Paramagnetic materials

   ii) Ferromagnetic materials

   iii) Anti-ferromagnetic materials

   iv) Ferrimagnetic materials

11. **Define Diamagnetic materials.**

In a diamagnetic material the electron orbits are randomly oriented and the orbital magnetic moments get cancelled. Similarly, all the spin moments are paired (having even no. of electrons).Therefore, the electrons spins in two opposite directions and hence the net magnetic moment is zero.These materials are called as diamagnetic materials.

Ex : Gold, Ge, Si, Antimony, Bismuth, Silver, Lead, Copper, Hydrogen,Water and Alcohol.

12. **Define Paramagnetic Materials.**

Paramagnetism is due to the presence of a few unpaired electrons. In the absence of external magnetic field, the magnetic moment (dipoles) are randomly oriented and posses very less magnetization in it.

Ex: Platinum, $CuSO_4$, $MnSO_4$, Palladium, Chromium, Aluminium, etc.

13. **Define Ferromagnetic materials.**

Ferromagnetism is due to the presence of more unpaired electrons.Even in the absence of external field, the magnetic moments align parallel to each other, so that it has large magnetism.This is called spontaneous magnetization.

Ex: Iron, Cobalt, Ni.

14. **What are the properties of Ferromagnetic materials?**

- All the magnetic lines of force pass through the material.
- Its susceptibility is high positive and it is given by $\chi = [C / (T - \theta)]$
- The permeability is very much greater than one.
- They have enormous permanent dipole moment.
- When the temperature is greater than the Curie temperature, then the Ferromagnetic becomes paramagnetic.
- The ferromagnetic material has equal magnitude dipoles aligned parallel to each other.

15. **What are magnetic domains?**

A ferromagnetic material is divided into a large number of small regions called domains. Each direction is spontaneously magnetized. The direction of magnetization varies from domain to domain and the net magnetization is zero in the absence of external magnetic field. The boundary line which separates two domains is called domain wall or Bloch wall.

16. **How the external magnetic field helps the magnetization in ferromagnetic material?**

When the magnetic field is applied to the Ferromagnetic material, the magnetization is produces in two ways.

i) By the motion of domain walls. ii) By the rotation of domains.

17. Define Exchange Energy.

The energy which makes the adjacent dipoles to align themselves is known as exchange energy. It is also called as magnetic field energy or magnetostatic energy. It arises from interaction of electron spins and it depends upon the interatomic distance.

18. What is Anisotropy energy?.

Crystals are anisotropic. The excess energy required to magnetize a material in particular direction over that required to magnetize it along the easy direction is called Anisotropy energy.

19. What is Domain wall energy (or) Bloch wall energy?

It is a transition layer which separates the adjacent domains, magnetised in different directions.

20. What is Magnetostriction energy?

When the domains are magnetized in different directions, they will either expand or shrink. i.e., Change in dimension when it is magnetized. The energy produced in this effect is called magnetostriction energy. It is the energy due to the mechanical stresses generated by domain rotations.

21. Define Hysteresis.

Hysteresis means "Lagging behind". i.e., The Lagging of magnetic induction behind the intensity of magnetic field (H) which is applied is called Hysteresis.

22. What is meant by Hysteresis Loss?

When the specimen is taken through a cycle of magnetization, there is loss of energy in the form of heat. This is known as Hysteresis Loss.

23. Define Retentivity and Coercivity.

During the process of demagnetization, the material retains some amount of magnetism, eventhough when intensity of magnetic field is zero. It is known as Retentivity or residual magnetism.

The amount of intensity of magnetic field applied in the reverse direction to remove the retentivity is known as coercivity or coercive force.

24. Distinguish between Soft and Hard magnetic material.

S. No.	Hard Magnets	Soft Magnets
1.	Cannot be easily magnetised.	Can be easily magnetised.
2.	Domain wall does not move easily and require large value of H for magnetisation.	Domain wall move easily and requires small value of H for magnetisation.
3.	Hysteresis loop area is large.	Hysteresis loop area is small.
4.	Permeability values are low.	Permeability values are high.
5.	Retentivity and Coercivity are large.	Retentivity and Coercivity are small.
6.	High eddy current loss.	Low eddy current loss.
7.	Irregularities will be more.	No irregularities.
8.	Examples Cunife, Cunico, Alnico, Chromium steel, tungsten steel, carbon steel.	Examples Iron–silicon alloy, Ferrous nickel alloy, Ferrites, Garnets.
9.	Uses : Permanent magnets	Uses : Electro magnets, computer data storage.

25. Define Energy product.

It is the product of retentivity (B_r) and coercivity (H_c).

Energy product $= B_r \times H_c$. It gives the maximum amount of energy stored in the specimen.

26. Define Antiferromagnetic materials.

Magnetic materials in which, the spins are aligned in anti-parallel manner due to unfavourable exchange interaction among them resulting in zero magnetic moment are called as Anti ferromagnetic materials.

27. What are Ferrimagnetic materials or Ferrrites?

Ferrrimagnetic materials are much similar to ferromagnetic materials in which the magnetic dipoles are aligned anti-parallel with unequal magnitudes. If small value of magnetic field is applied, it will produce the large value of magnetization.

28. Mention the properties of Ferrites.

1. The susceptibility is very high and positive.

2. The susceptibility decreases beyond Neel temperature.
3. Ferrites have high resistivity [10^{11} ohm -metre].
4. They have low eddy current loss.
5. They have high Permeability.
6. They are poor conductors.
7. They have low dielectric loss.
8. They have large hysteresis loss.

29. Define the terms Gyrator, Circulator and Isolator.

- **Gyrator :** It transmits the power freely in both directions with a phase shift of 'π' radians.
- **Circulator**: It provides sequential transmission of power between the ports.
- **Isolator**: It is used to display differential attenuation.

30. What are Magnetic bubbles?

Magnetic bubble is the direct access storage medium. Magnetic bubbles are soft magnetic materials with magnetic domains of a few micro metre in diameter. These bubbles are the electric analogue of the magnetic disk memories used in computers.The magnetic disk in the hard disk memory is moved mechanically where as the bubbles in a bubble memory device are moved electronically at very high speeds.

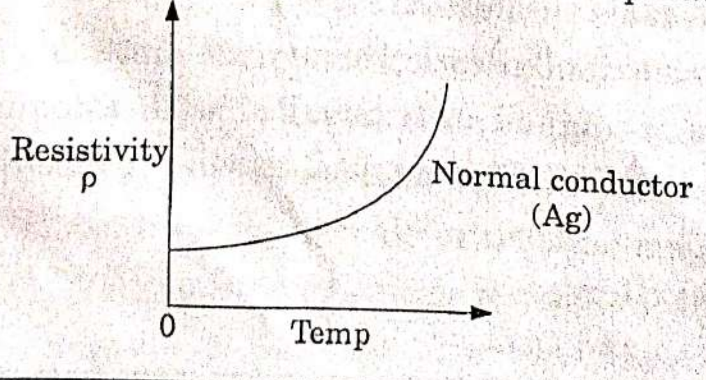
31. What is Supercondcutivity?

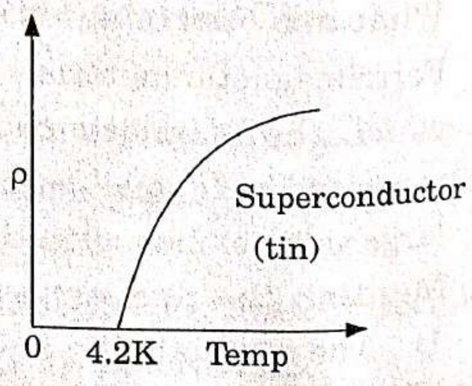
The ability of certain metals and alloys to exhibit almost zero electrical resistivity, when they are cooled to low temperature is known as superconductivity.

(ie.,maximum conductivity with zero resistance at low temperatures).

32. How the resistivity of normal and superconductor varies with temperature?

Variation of Resistivity with Temperature





- For a Normal conductor (Ag), the resistivity decreases when temperature decreases. At 0K, it has some resistivity value.
- For a superconductor (tin) the resistivity suddenly falls to zero at 4.2 K, when temperature is decreased.

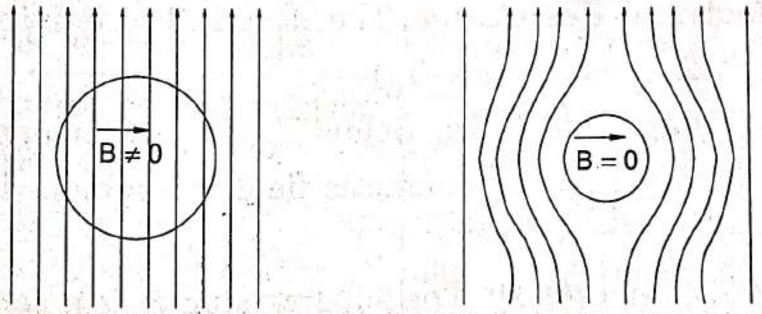
33. Define Critical Temperature.

Critical temperature (or)Transition temperature (T_C) is defined as the temperature at which the resistivity falls to zero. The temperature at which the normal conductor becomes a superconductor is known as critical temperature (T_C). Below T_C, the material (Tin) is in the superconducting state and above T_C, it is in the normal state.

34. What is Meissner effect? or Define Diamagnetic property.

When a weak magnetic field is applied to a superconducting specimen at a temperature below transition temperature T_c, the magnetic flux lines are expelled. The specimen acts as an ideal diamagnet. This effect is called "Meissner effect".

When a superconducting material is kept in a magnetic field $H > H_C$ at temperature $T > T_C$, the magnetic lines of force penetrate normally through the material as in Fig. 3.2 (a).



$T > T_c$ and $H > H_c$
(a) Normal state

$T < T_c$ & $H < H_c$
(b) Superconducting state

35. Define Critical magnetic field.

At any temperature below T_c, the minimum magnetic field required to destroy the superconductivity is called Critical magnetic field (H_C) of the material.

The critical magnetic field is $H_C = H_o \left[1-\left(\frac{T}{T_c}\right)^2\right]$

36. What happens in a superconductor when a heavy Current flows?

The superconducting property disappears when a heavy current flows, since