3. Magnetic Properties of Materials

3.1. Introduction

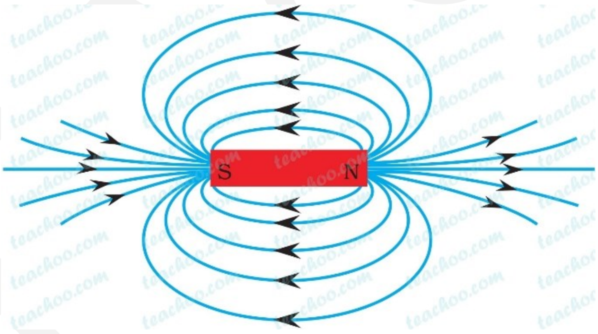
A very large number of modern devices depends upon magnetic properties of materials for their working. For example, the speakers, electrical power generators, electrical machines, transformers, television, data storage devices like magnetic tapes and disks, magnetic compass etc., Magnetic Resonance Imaging (MRI) scan is an important non-invasive diagnostic tool used in the medical field. Understanding the origin of magnetism and behaviour of magnetic materials will be helpful not only in the selection of suitable materials for a particular application but also in proper utilization of such devices. Further, it is highly useful in designing new applications of these materials.

3.2. Magnetism in materials

It arises from the magnetic moment or magnetic dipole of the magnetic materials. When an electrons revolves around the positive nucleus, orbital magnetic moment arises. Similarly when the electron spins, spin magnetic moment arises. Materials which can be magnetised by an external magnetic field are called magnetic materials.

The space around the magnet or the current carrying conductor where the magnetic effect is felt is called magnetic field.

Magnetic line of force is a continuous curve in a magnetic field as shown in figure.



The tangent at any point of this curve gives the direction of resultant intensity at that point. All the molecules of a material contain electrons rotating around the nucleus. These orbits are equivalent to circulating currents. So they produce a magnetic motive force (MMF). MMF is a force which produces the magnetic effect.

In most of the molecules, each MMF due to an individual orbit is neutralized by an opposite one. But, in the magnetic materials like iron and steel, there are number of unneutralized orbits. Then, the resultant axis of MMF produces a magnetic dipole.

In unmagnetized specimens, the molecular MMF axes lie along continuous closed paths. Therefore, no external magnetic effect can be found.

In magnetic specimens, the magnetic dipoles will line up parallel with the exciting MMF. When the exciting MMF is removed, the magnetic dipoles may remain aligned in the direction of the external field. Thus it produces permanent magnetism.

3.3. Basis definition

Magnetic dipole moment (m)

It is the product of magnetic pole strength and the distance between the two poles.

Magnetic flux (Φ)

Total number of magnetic lines of force passing through a surface is known as magnetic flux (Φ). Unit: Weber.

Magnetic flux density (or) Magnetic induction (B)

Magnetic flux density at any point in magnetic field is defined as the magnetic flux (Φ) passing normally through unit area of cross section (A) at that point.

Formula: $B = \frac{\phi}{A}$ Unit: Weber / meter ^{2} (or) Tesla

Intensity of magnetization

The term magnetization means the process of converting a non-magnetic material into a magnetic material. When an external magnetic field is applied to the metals such as iron, steel, some alloys etc., they are magnetized to different degrees. The intensity of magnetization (I) is the measure of magnetization of magnetised specimen. It is defined as the magnetic moment per unit volume of the material.

$$\text{Intensity of magnetization (I)} = \frac{\text{Magnetic moment (M)}}{\text{Volume(V)}}$$ Unit: Weber / meter^2.

Magnetic field intensity (or) strength (H)

It is the force experienced by a unit North Pole placed at any point in the magnetic field. Unit: Newton per weber (N/Wb) (or) Ampere turns per meter (A/m)

Magnetic permeability (μ)

Magnetic permeability of a substance measures the degree to which the magnetic field can penetrate through the substance. It is found that magnetic flux density (B) is directly proportional to the magnetic field strength (H)

$B \propto H$

(or) $B = \mu H$

Where μ is the proportionality constant called permeability (or) absolute permeability of the medium

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

"Permeability of a substance is the ratio of magnetic flux density (B) inside the substance to magnetic field intensity (H)".

Absolute permeability of a medium (or)a material is also defined as the product of permeability of a free space (μ_0) and the relative permeability of the medium (μ_r)

i.e., $\mu = \mu_0 \times \mu_r$

where unit of permeability is Henry / meter.

Relative Permeability (μ_r) of the medium

It is the ratio between absolute permeability of the medium (μ) to the permeability of a free space (μ_0). This is purely a number and has no unit. For air and non-magnetic material, its value is '1'

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

Magnetic susceptibility (χ)

Magnetic susceptibility of a specimen is a measure of how easily a specimen can be magnetised in a magnetic field. It is defined as the intensity of magnetization produced in the substance per unit magnetic field strength (H)

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

It is a dimensionless quantity because both I and H have same units

Magnetic induction in a given magnetic material for the applied field strength 'H' is given by

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

(or) $B = \mu_0 H (1 + \frac{I}{H})$

(or) $\frac{B}{H} = \mu_0 (1 + \chi)$

(or) $\mu = \mu_0 (1 + \chi)$

(or) $\frac{\mu}{\mu_0} = (1 + \chi)$

(or) $\mu_r = 1 + \chi$

(or) $\chi = \mu_r - 1$

3.4. Atomic magnetic moments

The fundamental reason for the response of a material to an external magnetic field is that the atoms possess magnetic moments. That is, each atom acts like a tiny magnet. There are two source that contribute to atomic magnetic moment.

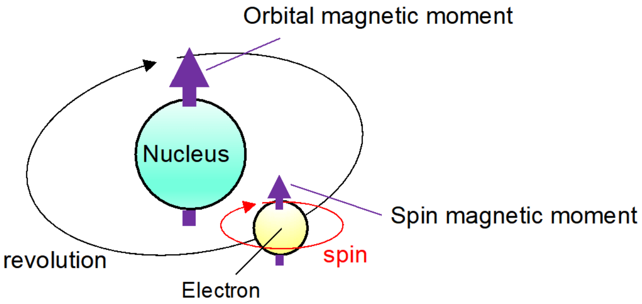
(i) Magnetic moment due to the movement of electrons in orbits around the nucleus, i.e., due to orbital angular momentum. This is called the orbital magnetic moment.

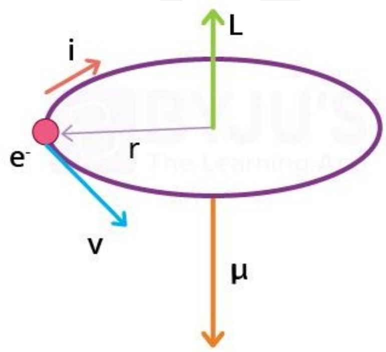
(ii) Magnetic moment due to spin of the electrons, i.e., due to spin angular momentum . This is called spin magnetic moment.

(iii) in addition to the above two contribution, there is a small contribution due to spin angular momentum of the nucleus called the nuclear magnetic moment. But the nuclear magnetic moments are very much smaller and so their interaction of the electronic magnetic moment.

Magnetic moment due to orbital angular momentum of electrons.

The orbital motion of electron revolving about a nucleus is equivalent to a tiny current loop. This produces a magnetic moment perpendicular to the plane of the orbit as shown in figure.





Derivation

<u>Orbital angular momentum of the electrons:-</u> μ_0

Consider an electron revolving in an orbit with radius 'r' moving with linear velocity 'v' and produces a constant angular velocity 'ω'. Let T be time taken for one revolution and 'e' be the magnitude of charge on the electron.

The current across any point in the orbit is $I = \frac{\text{Charge of electron (-e)}}{\text{Time (T)}}$ (1)

But $T = \frac{2\pi}{\omega}$ (2)

Any electron revolving around orbit produces magnetic field perpendicular to its plane which produces an orbital magnetic moment given by

$$\mu_0 = IA \qquad (3)$$

$$= \left(\frac{e\omega}{2\pi}\right)\pi r^2$$

But v = rω and $\omega = \frac{v}{r}$ (4)

$$\therefore \mu_0 = \left(\frac{evr}{2}\right)$$

$$= -e\left(\frac{mvr}{2m}\right) \qquad \mu_0 = \left(\frac{-eL}{2m}\right) \qquad (5)$$

where L = m v r

Equation (5) represents the expression for the magnetic moment associated with the orbital motion of the electron.

The negative sign indicates that the orbital magnetic moment and angular momentum lie in opposite direction.

Bohr magneton

The magnetic moment contributed by an electron with angular momentum quantum number n = 1 is known as Bohr magneton.

We know that $\mu_0 = \left(\frac{-eL}{2m}\right)$

According to quantum theory, orbital angular momentum is $L = n\hbar$

(or) $L = \frac{nh}{2\pi}$ since $\hbar$ $\frac{h}{2\pi}$ and n is the orbital angular momentum quantum number.

Substituting the above values and considering the electrons in ground state ($n = 1$)

The magnetic moment in terms of Bohr magneton is given by $\mu_B = \left(\frac{eh}{4\pi m}\right)$

By substituting the values of *h, m* in the above equation, we get Bohr magnetron given by μ_B = 9.27 x 10^{-24} Am^2

<u>Electron spin magnetic moment</u> (μ_S)

In an atom, every two electrons will form a pair with opposite spins. Thus the resultant spin magnetic moment is zero. But in magnetic materials, the unpaired electrons spin magnetic moments interacts with the adjacent atom's to form unpaired electron spin magnetic moment which is responsible for ferro and paramagnetic behaviour of materials. Accordingly to Quantum theory, spin magnetic moment $\mu_S = \frac{e}{m}\mathbf{S}$

Where $\mu_S = \pm 1$ Bohr Magnetron.

<u>Nuclear spin magnetic moment</u> (μ_N)

The mass of the nucleus is larger than that of electron by a factor of the order of 10^3. Hence, nuclear spin magnetic moment is of the order of 10^{-3} Bohr magnetron.

Since μ_S and μ_N are very small, then the practical purpose, the total magnetic moment arises due to spin magnetic moment.

3.5. Classification of magnetic materials

Magnetic materials can be classified into two categories based on existence of dipole moment and the response of dipole moment and the response of magnetic material to external magnetic fields namely

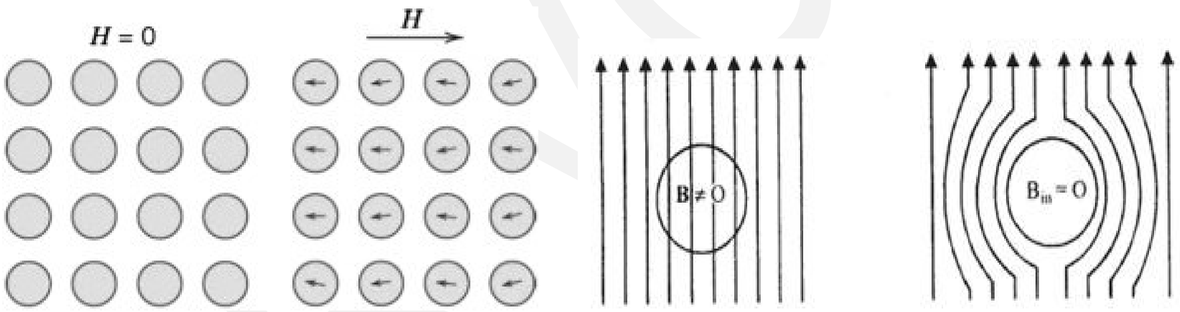
(1) **Diamagnetic materials** - no permanent magnetic moment

(2) **Paramagnetic, ferromagnetic, antiferromagnetic and ferrimagnetic materials** – having permanent magnetic moment.

Diamagnetism

Diamagnetism is exhibited in all materials. The atoms in diamagnetic materials do not possess permanent magnetic moments. However, when the diamagnetic material is placed in an external magnetic field, the electrons in the atomic orbits tend to counteract the external magnetic field. Hence, the atoms require an induced magnetic moment.

As a result, the material becomes magnetised. The direction of the induced dipole moment is opposite to that of externally applied magnetic field. Due to this effect, the material is very weakly repelled in magnetic field. This phenomenon is known as diamagnetism.



When the magnetic field *H* is zero, the atom possess zero magnetic moment as shown in figure. But, when the magnetic field is applied in the direction as shown in figure, the atoms acquire an induced magnetic moment in the direction opposite to that of the magnetic field.

The strength of induced magnetic moment is proportional to the applied field and hence the magnetisation of the material varies directly with the strength of the magnetic field.

The induced dipoles and magnetization vanish as soon as the applied magnetic field is removed. The susceptibility of the diamagnetic material is negative. Due to this, the material is weakly repelled in the magnetic field.

Definition

The diamagnetism is the phenomenon by which the induced magnetic moment is always in the opposite direction of the applied magnetic field.

Properties

(1) Diamagnetic materials repel the magnetic lines of force.

(2) There is no permanent dipole moment. Therefore magnetic effects are very small in these material.

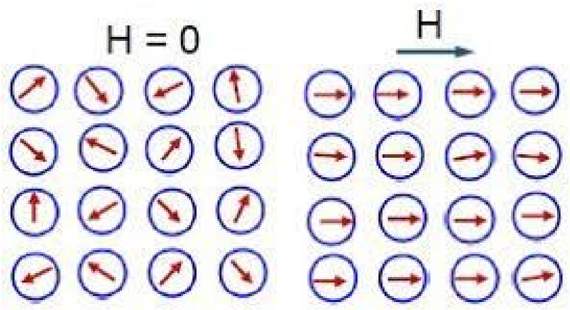
(3) The magnetic susceptibility is negative and it does not depend on temperature and applied magnetic field strength

Example: Gold, germanium and silicon.

Paramagnetism

In certain materials, each atom or molecule possesses a net permanent magnetic moment (due to 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 as shown in figure. This makes the net magnetic moment zero and hence the magnetisation of the material is zero.

But, when an external magnetic field is applied, the magnetic dipoles tend to align themselves in the direction of the magnetic field as shown in figure and the material gets magnetised. This effect is known as paramagnetism.



With an increase in temperature, increase in thermal agitation disturbs the alignment of the magnetic moments. It tends to randomize the dipole direction thus leading to decrease in magnetization. This indicates that the paramagnetic susceptibility decrease with increase in temperature. It is noted that the paramagnetic susceptibility varies inversely with temperature

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

(or) $\chi = \frac{C}{T}$

This is known as Curie's law of paramagnetism. C is a constant called Curie's constant.

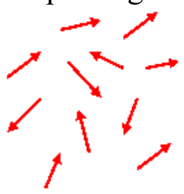
Definition

The Paramagnetism is the phenomenon by which the orientations of magnetic moments are largely dependent on temperature and applied field. If the applied magnetic energy is greater than the thermal energy, the magnetic moment of the material is finite and large.

Properties

- The paramagnetic materials attracts the magnetic lines of force.
- They possess permanent dipole moment

- The value of susceptibility is positive and it depends on temperature.
- $\chi = \dfrac{C}{T-\theta}$
- The spin alignment of paramagnetic materials is like



- Example: Ferric oxide, ferrous sulphate, nickel sulphate.

Ferromagnetism

Certain metals like iron (Fe), Cobalt (Co), Nickel (Ni) and certain alloys exhibit high degree of magnetisation.

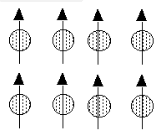
These materials show the spontaneous magnetisation. i.e., they have magnetization (atomic magnetic moments are aligned) even in the absence of an external magnetic field. This indicates that there is a strong internal field within the material which makes the atomic magnetic moment align with each other. This phenomenon is known as ferromagnetism.

Definition

Ferromagnetism is a phenomenon by which spontaneous magnetization occurs when $T \leq T_c$ *and so even in the absence of applied filed, the magnetic moments are enormous. Here* T_c *is the curie temperature of the material.*

Properties

- All the dipoles are aligned parallel to each other due to the magnetic interaction between the dipoles.
- They have permanent dipole moment. They are strongly attracted by the magnetic field.
- They exhibit magnetisation even in the absence of magnetic field.
- They exhibit hysteresis (lagging of magnetization with the applied magnetic field).
- On heating, they lose their magnetisation slowly.
- The dipole alignment is as shown in figure

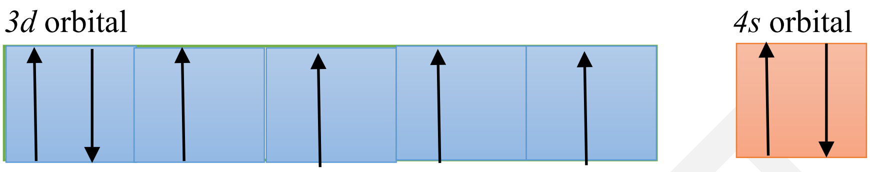


- The magnetic susceptibility is very high and it depends on temperature which is given by $\chi = \dfrac{C}{T-\theta}$ for ($T > \theta$, paramagnetic; $T < \theta$, ferromagnetic). Here C is Curie's constant.

3.6. Origin of ferromagnetism and exchange interaction

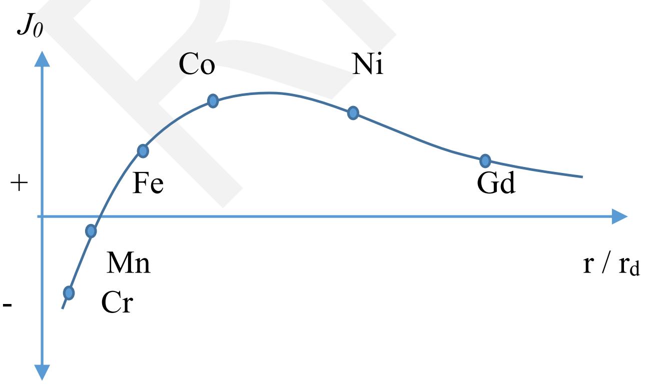
The ferromagnetic property is exhibited by transition elements such as iron, cobalt and nickel at room temperature and rare earth elements like gadolinium and dysprosium.

The ferromagnetic materials possess parallel alignment of dipoles. This parallel alignment of dipoles is not due to the magnetic force existing between any two dipoles. The reason is that the magnetic potential energy is very small and it is smaller than thermal energy.
The electronic configuration of iron is $1s^2$, $2s^2$, $2p^6$, $3s^2$, $3p^6$, $3d^6$, $4s^2$. For iron , the 3*d* sub shell is an unfilled one. This 3*d* subshell have five orbitals. For iron, the six electron present in the 3*d* subshell occupy the orbitals such that there are four unpaired electrons and two paired electrons as shown in figure.



These four unpaired electrons contribute a magnetic moment of $4\mu B$. This arrangement shows the parallel alignment of four unpaired electrons. The parallel alignment of dipoles in iron is not due to the magnetic interaction. It is due to the Pauli's exclusion principle and electrostatic interaction energy. **The Pauli's exclusion principle and electrostatic interaction energy are combined together and constitute a new kind of interaction known as exchange interaction. The exchange interaction is a quantum mechanical concept.** The exchange interaction between any two atoms depends upon the interatomic separation between the two interacting atoms and the relative spins of the two outer electrons. The exchange interaction between any atoms is given by $E_{ex} = -J_e S_1 S_2$
Where J_e is the numerical value of the exchange integral, S_1 *and* S_2 are the spin angular momenta of the first and second electrons. The exchange integral value is negative for the number of elements. Therefore, the exchange energy value is negative when the spin angular momentum S_1 *and* S_2 are opposite direction. Hence antiparallel alignment of diploe is favoured. This explains the antiparallel alignment of dipoles in antiferromagnetic materials.

In some materials like iron, cobalt and nickel the exchange integral value is positive. The exchange energy is negative when the spin angular momentum is in the same direction. This will produce a parallel alignment of dipoles. A plot between the exchange integral and the ratio of the interatomic separation of the radius of 3*d* orbital (r/r_d) is shown in figure.



For the transition metals like iron, cobalt, nickel and gadolinium the exchange integral is positive, whereas for manganese and chromium the exchange integral is negative. The positive value of the exchange integral represents the material is ferromagnetic and the negative exchange integral value represents the material us antiferromagnetic. In general, if the ratio, $r/r_d > 3$, the material is ferromagnetic, otherwise it is antiferromagnetic.

3.7. Saturation magnetization and Curie temperature

Definition

The maximum magnetization in a ferromagnet when all the atomic magnetic moments are aligned is called the saturation magnetization M_{sat}.

When temperature is increased, lattice vibrations become more energetic which leads to a disruption of the alignments of the spins. The spins cannot align perfectly with each other. The lattice vibration may be sufficient to disorientate the spin of the atom. The ferromagnetic behaviour disappears at a critical temperature called the Curie temperature denoted by T_C. At this temperature the thermal energy of lattice vibrations in the crystal can overcome the potential energy of the exchange interaction and hence destroy the spin alignments. Above the Curie temperature, the ferromagnetic materials behaves like paramagnetic.
The saturation magnetization M_{sat} therefore decreases from its maximum value M_{sat} (0) at absolute zero temperature to zero at the Curie temperature. Figure shows the dependence of M_{sat} on the temperature when M_{sat} is normalized to M_{sat} (0) and temperature is the reduced temperature, that is T / T_C when $T / T_C = 1$, $M_{sat} = 0$. Since at the Curie temperature, the thermal energy kT_c is sufficient to overcome the exchange energy E_{ex}, then $E_{ex} = kT_c$
The Curie temperature (T_c) depends on the substance and it is well above the room temperature.
The susceptibility of ferromagnetic material is given by Curie-Weiss law:

Magnetic susceptibility $\chi = \dfrac{C}{T - T_C}$

Where C is Curie constant.

	Substance	T_C (K)	M_s (x 10^5 JT^{-1} m^{-3})	$\mu_0 M_s$ (T)
	Iron	1043	17.1	2.15
	Cobalt	1388	14.0	1.76
	Nickel	627	4.85	0.61
	Gadolinium	292	20.6	2.60
	CrO_2	386	5.18	0.65

3.8. Domain theory of ferromagnetism

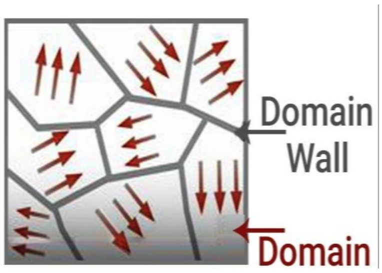
Weiss proposed the concept of domains in order to explain the properties of ferromagnetic materials.

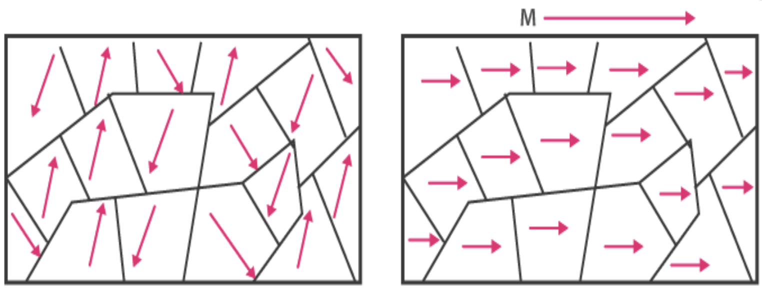
Principle

The group of atomic dipoles (atoms with permanent magnetic moment) organised in tiny bounded region in the ferromagnetic materials are called magnetic domains.

Explanation

Ferromagnetic materials contains a large number of domains. In each domain, the magnetic moments of the atoms are aligned in same direction. Thus, the domain is a region of the ferromagnetic material in which all the magnetic moments are aligned to produce a net magnetic moment in one direction only.





A. Random domain orientation   B. After magnetization

Thus, it behaves like a magnet with its own magnetic moment and axis. In a demagnetized ferromagnetic material, the domains are randomly oriented as shown in figure. So that the magnetization of the material as a whole is zero. The boundaries separating the domains are called *domain walls*. These domain walls are analogous to the grain boundaries in a polycrystalline material.

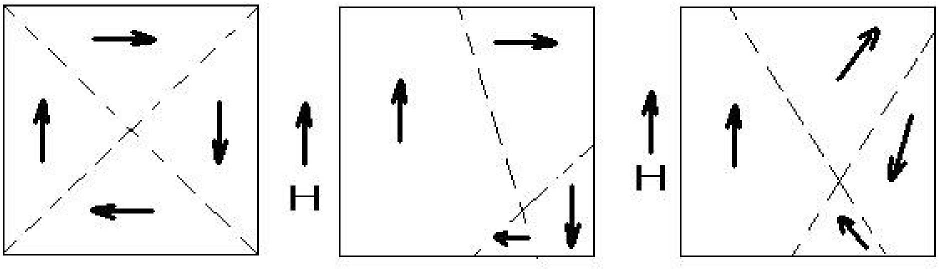
However, the domain walls are thicker than the grain boundaries. Like grain growth, *the domain size* can also grow due to the movement of domain walls. When a magnetic field is applied externally to a ferromagnetic material, the domains align themselves with field as shown in figure. This results in a large net magnetization of the material.

Process of domain magnetization

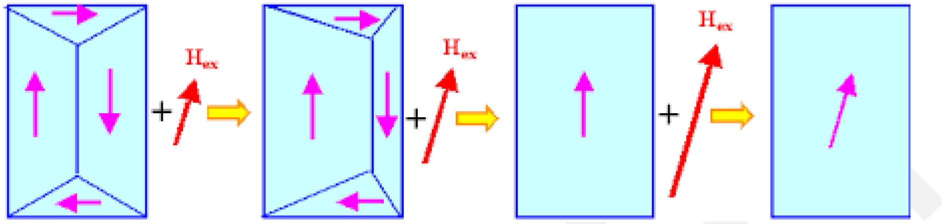
We know that in an unmagnetized specimen, the domains are randomly oriented and the net magnetization is zero. When the external magnetic field is applied, domains align with the direction of field resulting in large net magnetization of a material. There are two possible ways in which the domains are aligned in the external field direction.

(a) By the motion of domain walls

Figure (a) shows an unmagnetized specimen in which domains are randomly aligned. When a small magnetic field is applied, the domains with magnetization direction parallel or nearly parallel to the field, grow at the expense of others as shown in figure (b). This domain growth occurs due to the movement of domain walls away from the minimum energy state.



H=0
(a) (b) (c)

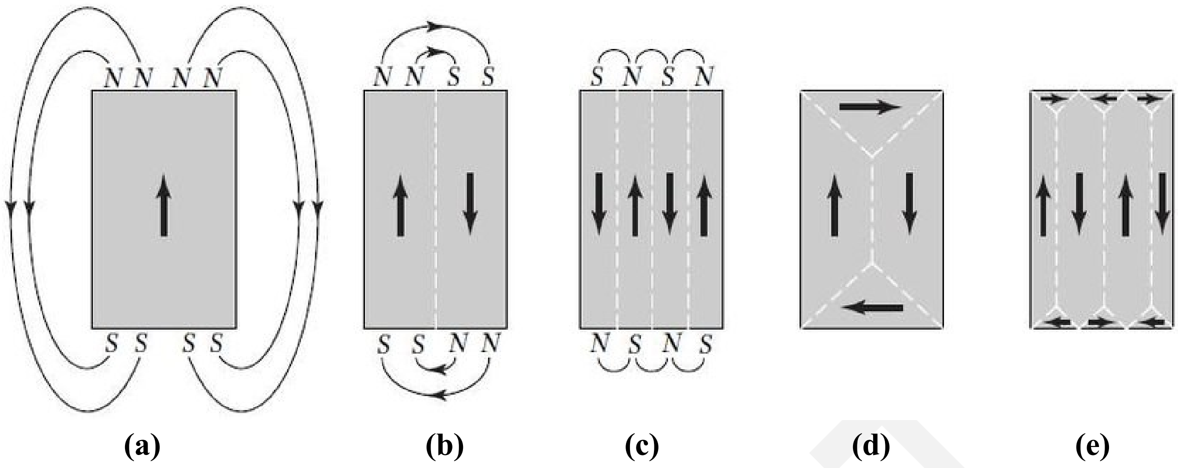


(b) By rotation of domains
As the magnetic field is increased to a large value (i.e., near saturation) further domain growth becomes impossible through domain wall movement. Therefore, most favourably oriented and fully grown domains tends to rotate so as to be in complete alignment with the field direction as shown in figure.

Origin of domains
We know that according to thermodynamics, the free energy of a solid tends to reach a minimum. It is found that the domain structure occurs in order to minimise the total energy of ferromagnetic solid.

3.9. Types of energy involved in the process of domains growth
To study the domain structure clearly, we must know four types of energy involved in the process of domain growth. They are:
(1) Exchange energy
(2) Magnetostatic energy
(3) Crystal anisotropy energy
(4) Magnetostrictive energy

(1) Exchange energy
It is energy associated with the quantum mechanical coupling that aligns the individual atomic dipoles within a single domain. It arises from interaction of electron spins. It depends upon the interatomic distance. Figure (a) shows a cross section through ferromagnetic crystal having a single domain structure established by exchange energy with a saturation.

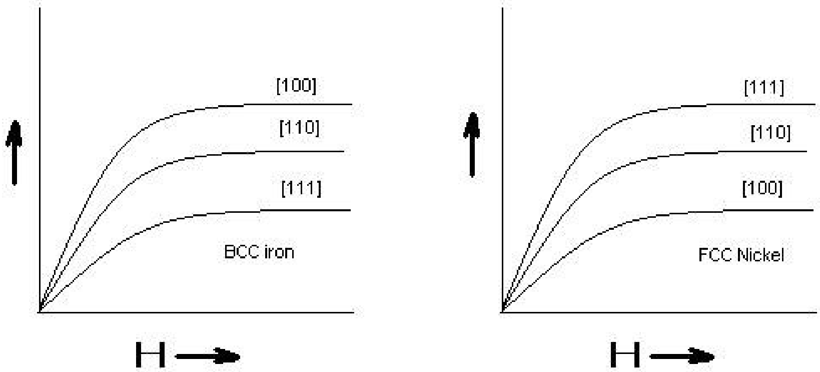


(2) Magnetostatic energy

Magnetostatic energy or magnetic potential energy is the energy present in any ferromagnetic material when the material produces an external field. The magnetic energy of the specimen can be reduced by dividing the single domain into two domains as shown in figure (b). Further, subdivision into N domains (figure c) reduces the magnetic energy to 1/N of the magnetic energy of the material with single domain.

(3) Crystal anisotropy energy

It is the energy of magnetization which is the function of crystal orientation. In the below figure magnetization curves for iron with applied field along different crystallographic direction and different crystal structure are shown (BCC & FCC)



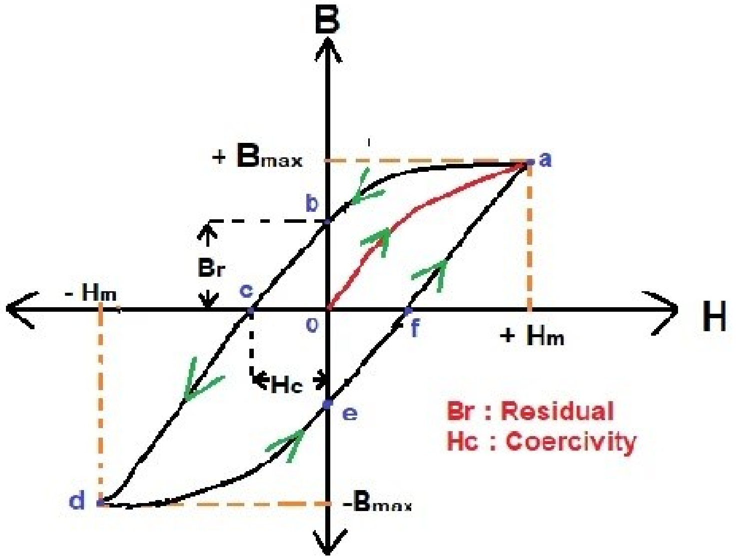
From the figure, it is clear that, BCC iron require much greater fields to produce magnetic saturation in [111] direction as compared to the field required in [100] direction. Here the difference in magnetic energy to produce magnetic saturation in an easy [100] direction and [111] direction is called *crystal anisotropic energy*.

(4) Magnetostrictive energy

When a material is magnetised, it is found that it suffers a change in dimensions. This phenomenon is known as magnetostriction. This deformation is different along different crystal direction. So if the domains are magnetised 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.

3.10. Hysteresis M – H Behaviour of Ferromagnetic materials

A graph is drawn by plotted magnetic field strength 'H' along X-axis and magnetic induction 'B' along Y-axis as shown in fig below.



- ❖ 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 magnetization.(**Saturation Magnetization - B_{sat}**)
- ❖ The value of magnetic field is decreased, but the magnetic induction does not decrease at the same rate at which it is increased. When H=0, $B \neq 0$, the magnetic induction has a definite value represented by OB and it is known as **retentivity**.
- ❖ 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 it is known as **coercivity**.
- ❖ 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 magnetization. The loop ABCDEFA 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**.

<u>Retentivity or residual magnetism</u>

Retentivity or residual magnetism is the amount of magnetic induction retained in the material after removing the magnetizing field. It is represented by OB in the B-H curve (fig)

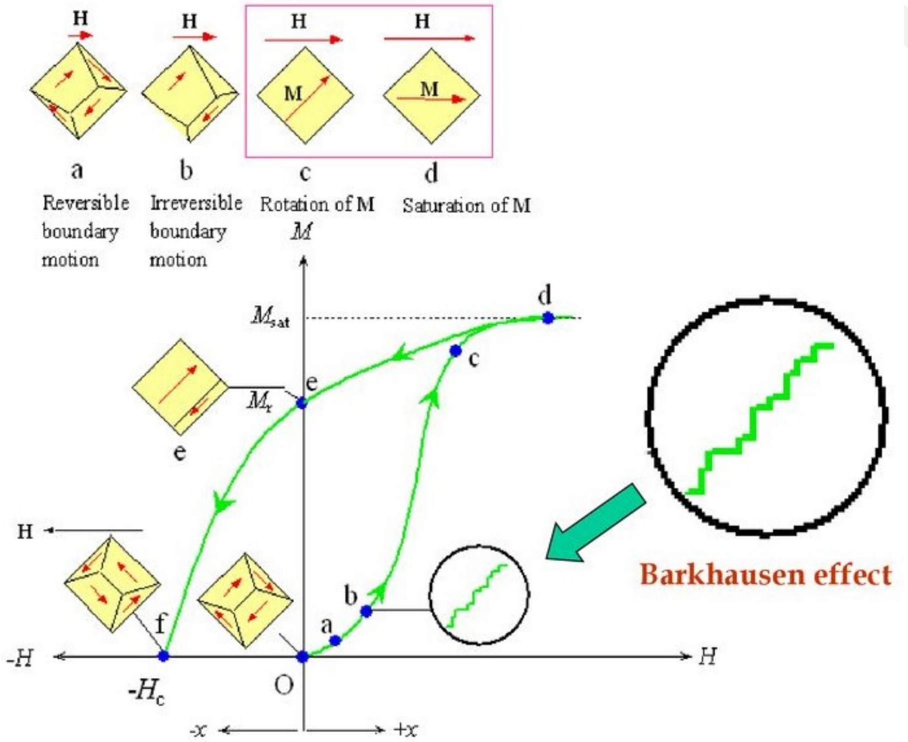
Coercivity or Coercive force

Coercivity or coercive force is the amount of magnetizing 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)

Hysteresis loss

When a specimen is taken through a cycle of magnetization, then 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.

3.10. Hysteresis behaviour based on domain theory



When a Ferromagnetic is subjected to external field, there is an increase in the value of the resultant magnetic moment due to

(i) The movement of domain walls

(ii) The rotation of domains

When a weak external field is applied, the domain walls are displaced slightly in the soft direction of magnetization. This gives rise to small magnetization corresponding to the initial portion of the hysteresis curve (OA) as shown in figure .Now, if applied field is removed, then the domains return to its original state and it is known as "**Reversible Domains**".

When a strong external field is applied, large number of domains contributes to the magnetization and thus the magnetization increases rapidly with "H"↑

Here, 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 Figure and this domains are called **"Irreversible Domains".**

At point "B" all the domains have got magnetized along the soft direction. Now, when the field is further increased, the domains start rotating along with the field direction and the anisotropic energy is stored in the "*Hard Direction*" represented as "BC" in figure

Thus the specimen is said to attain the maximum magnetization 'M_s'. At this position, even after the removal of external field the material possess residual magnetization called **"Retentivity"** represented by "OE" in figure

Actually after 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 spend to reduce the magnetization to zero is called **"Coercivity"** represented by "OF" in figure

Hysteresis Loss:

It is the loss of energy in taking a ferromagnetic specimen through a complete cycle of magnetization and the area enclosed is called "Hysteresis Loop". Based on this area of hysteresis, the magnetic are classified as soft and hard magnetic materials.

3.11. Antiferromagnetism

Antiferromagnetic materials are magnetic materials which exhibit a small positive susceptibility of the order of 10^{-3} to 10^{-5}. The variation of susceptibility with temperature shows a peculiar pattern in these materials. The susceptibility increases with increasing temperature and it reaches a maximum at a certain temperature called Neel temperature T_N. With further increase in temperature, the material reaches paramagnetic state. The material is antiferromagnetic below T_N. The transition temperature T_N lies far below the room temperature for most of the materials.

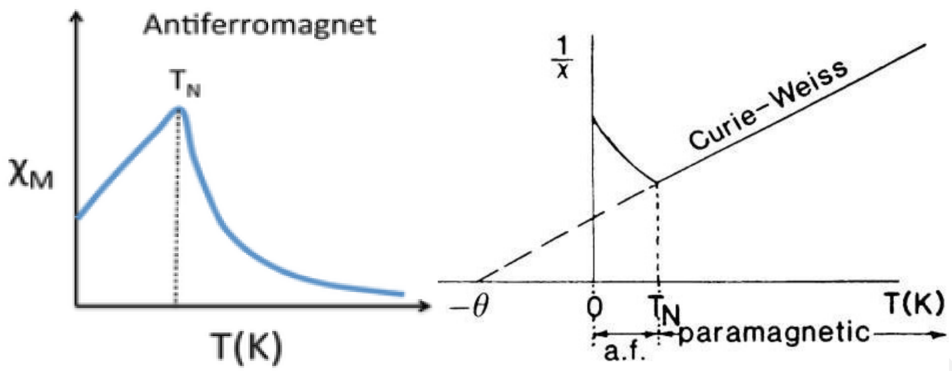
In the paramagnetic state, the variation of inverse susceptibility ($1/\chi$) with temperature is linear as shown in figure. The extrapolation of the paramagnetic line in figure to $1/\chi = 0$ yields a negative θ. Therefore, the variation of susceptibility with temperature obeys modified Curie-Weiss law.

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

Where θ – paramagnetic Curie temperature

C – Curie's constant.

In antiferromagnetism, the magnetic moments of sublattices in unit cell are equal in magnitude but opposite in direction, so they cancel out each other. This gives net zero magnetization.

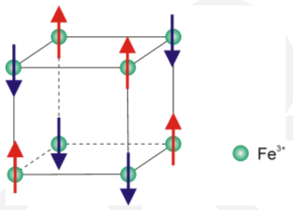


Definition

Any materials having the magnetic interaction between any two dipoles align themselves antiparallel to eachother are called antiferromagnetic materials.

Properties

- The adjacent dipoles align antiparallel and hence the net magnetic moment is zero
- The antiparallel alignment of adjacent dipoles is due to exchange interaction between them
- The magnitude of susceptibility is small an positive
- The susceptibility (χ) increases with increase in temperature upto Neel temperature (θ_N), Beyond the Neel temperature, the susceptibility decreases with temperature
- In antiferromagnetic materials, Neel temperature (θ_N) is the temperature at which susceptibility of the material is maximum.
- Example: Ferrous oxide, Manganese oxide and chromium oxide.



3.12. Ferrimagnetism

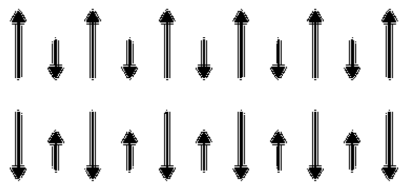
There are some magnetic materials in which the magnetic moments of two sub lattices are opposite in direction but not exactly equal in magnitude (because of two different types of ions in the lattices). Such crystals possess spontaneous magnetization and exhibit most of the properties of ferromagnetic materials. This uncompensated antiferromagnetism is known as ferrimagnetism.

Ferrimagnetic materials (or) ferrites

Substance which possess a spontaneous magnetization in which the magnetic moments of the two sub lattice are opposite in direction but not exactly equal in magnitude are called "Ferrites".

Properties

- Ferrites has net magnetic moment
- Above Curie temperature, it becomes paramagnetic and it behaves as ferrimagnetic material below Curie temperature.
- The susceptibility of ferrite is very large and positive. It depends on temperature. It is given by $\chi_{ferri} = \frac{C}{T \pm \theta}$ for $T > T_N$.
- Spin alignment is antiparallel of different magnitudes as shown in figure.



- Mechanically, it has pure iron character.
- They have high permeability and high resistivity
- They have low eddy current loss and low hysteresis loss.

Applications

- Hard magnetic ferrites are used in the manufacture of permanent magnets
- Such magnets are used in super high frequency technology.
- Soft magnetic ferrites are used in the production of cores for inductor coils used in telecommunication and low power transformers.
- Ferrites are used in magnetic flims in which demagnetization process occurs at the speed exceeding million times/second. This technology is important for electronics, automobiles and computer hardware engineering.
- Ferrites re used in information storage devices such as magnetic discs and tapes.
- Ferrite rods are used to produce ultrasonics by magnetostriction principle.
- Ferrite rods are used in radio receiver to increase sensitivity and selectivity.
- Since the ferrite has low hysteresis loss and eddy current loss, it is used in two port m microwave devices such as gyrator, circulator and isolator.

3.13. Types of magnetic materials

Magnetic materials are classified in to two types based on magnetization

(i) Soft magnetic materials (ii) Hard magnetic materials

Soft magnetic materials

Definition

Materials which are easy to magnetize and demagnetize are called soft magnetic materials.

These magnetic materials do not retain the alignment of magnetic domains after the removal of the external magnetic field.

Properties

- The soft magnetic materials can be magnetised and demagnetised easily.
- They have high permeability
- They have low residual magnetism
- They exhibit low hysteresis loss
- They have low hysteresis loss
- The magnetic energy stored is low

Examples:

- Pure or ingot iron
- Cast iron (carbon above 2.5%)
- Carbon steel
- Silicon steel
- Manganese and nickel steel
- Permalloy (Ni: Fe alloy = 78.15% : 21% + small quantities of Cr, Co, Cu and Mn)
- Mumetal (Ni =75.4%, Cu-4%, Cr-1.5% and remaining Fe)
- Perminar (Co-Ni-Fe alloy = 50%, 25%, 25%)
- Soft ferrites

Applications

- Cast iron is sued in the structure of electricity machinery and the frame work of DC machine
- Carbon steel has high mechanical strength and it is used in making motor of turbo alternators
- Silicon steel is used for the construction of poles of motor and dynamo and core plates of transformer
- Manganese and nickel steel is used for making cable boxes, meter cases and end rings of turbo alternators
- Permalloy is used as thin tape wrapped around the conductors of loaded submarine cables.
- Mumetal is used for making cores of transformers.
- Perminar is used in armatures of motors, transformer cores, etc.,

Hard magnetic materials

Definition

Materials which retain their magnetism and are difficult to demagnetize are called hard magnetic materials. These magnetic materials retain the alignment of the magnetic domains permanently even after the removal of external magnetic field

Properties

- The hard magnetic materials have low permeability and strongly repel the magnetic field
- They have high retentivity and coercivity
- They require high magnetising force to attain magnetic saturation
- They have large hysteresis loop area and large energy loss.
- The value of B – H product is high.

Examples

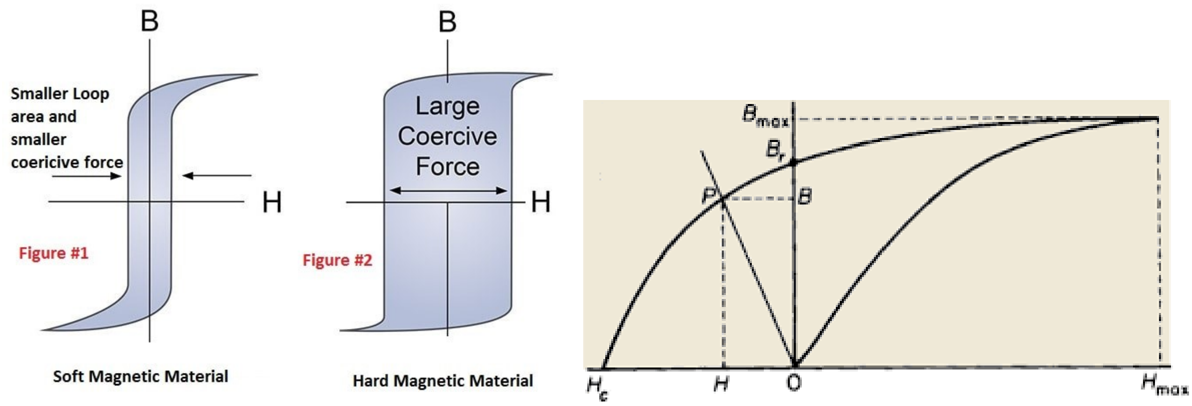
- **Tungsten steel**: it contains 4.5 to 6% tungsten, o.5 to 0.7% carbon and the remaining is iron.
- **Carbon steel**: It contains 34% cobalt, 5% chromium, 3.5 to 6% tungsten and remaining is iron.
- **Alini:** it contains 10 – 15% aluminium, 25-30% nickel and 65-75% iron.
- **Alinco**: It contains 18% nickel, 10% aluminium, 5% copper, 15% cobalt and remaining is iron.
- **Cunife**: It contains 50% copper, 30% nickel and 20% iron
- **Hypernic**: It contains 50% of nickel and 50% of iron.

Applications

- Tungsten steel is used in making permanent magnets for dynamos and motors.
- Cobalt steel is used in motors, fans and heavy duty instruments.
- Alini is used in the design of portable and light weight instruments
- Alnico is used for the production of permanent magnets in smaller size
- Cunife is useful in producing small size magnets.

Energy product

The product of retentivity (B_r) and coercivity (H_c) is known as energy product. It represents the maximum amount of energy stored in the specimen. Therefore, for permanent magnets the value of energy product should be very high as shown in figure.



3.14. Magnetic principle in computer data storage

In general memory units are the devices used to store the information in the form of bits. [8 bit =1 byte]

The memory units are classified as

(i) Main memory (or) Internal memory
(ii) Auxiliary memory (or) External memory

Main Memory:

The memory unit of CPU is called main memory. Thus data's are write and finally be erased if necessary.

Eg: EPROM, ROM, RAM etc.,

Auxiliary Memory:

This type of memory is also referred to as back-up storages because; it is used to store large volume of data on permanent basis. This date can be accessed or recopied if necessary.

Eg: Magnetic tapes, Magnetic disk, Ferrite core memories and Bubble memories.

1. Magnetic Tape:

The tape is a plastic ribbon with metal oxide material coated on one side which can be magnetized, in this information can be written and also can be read by write/read heads.

Information recorded in the tape is in the form of tiny magnetized and non-magnetized spots on the metal oxide coating. The magnetized spot represents '1' sun magnetized spot represent '0' in binary code. The information can be accessed, processed, erased and can be stored again in same area.

Advantages:-

- Storage capacity is large
- Easy to handle
- Loss expensive
- Erased and reused.

Disadvantages:-

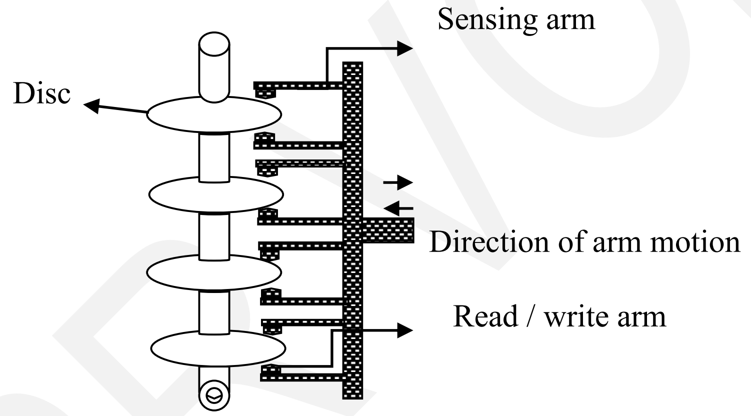
- It consumes lot of time.

2. Magnetic Disc Devices:

(A) Hard disk drives:

It is the direct access storage device made up of hard aluminum platters. This platter surface is carefully machined for flat. This surface is coated with magnetic oxides and built in to a bar.

Similar such disks are mounted on a vertical shaft, forming a disk pack as shown in figure. The drive mechanism drives the disc pack with the spindle. The data is written can read by the R/W heads in the horizontal sensing arms by moving in and out between the platters with the precaution that the R/W head doesn't touches the surface instead, it fly over the disk surface by a fraction of a mm.



Advantages:-

- It has large storage capacity.
- Thousand of files can be permanently stored.
- Very high speed in reading and writing the information
- This is prevented from dust, since they are sealed.

Disadvantages:-

- It is very costly
- If data is completed, there is a heavy loss.

(B) Floppy disc drives:

Floppy is made of a very thin and flexible plastic materials coated with magnetic materials. This disc is inserted in floppy disc drive for read/write operation by the read/write head in the disc. Size: 5.25” called mini floppy, 3.25” called micro floppy.

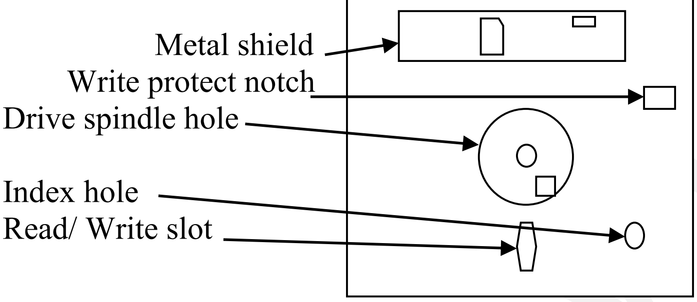
Organization:-

Surface of the floppy disc is divided into a number of concentric circles known as tracks where the information is recorded. The tiny magnetic spots are used to record the logic 1 (or) 0 state. The spot magnetized in one direction are ‘1’ state and in other direction are called ‘0’ state. Each track has number of sectors

Operation;-

When the floppy is put in drive unit. When drive is operated. The floppy disc is rotated which makes physical contact with read/write head. This magnetic material movement is controlled by serve mechanism.

Floppy Disc:-



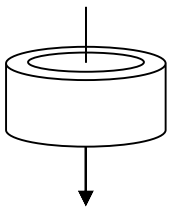
Advantages:-

(i) Storing and transporting of data is easier.
(ii) Cost is less
(iii) It can reused many times

Disadvantages:-

(i) Storage capacity is less
(ii) Care to be taken for handling.

3. Ferrite Core Memory:



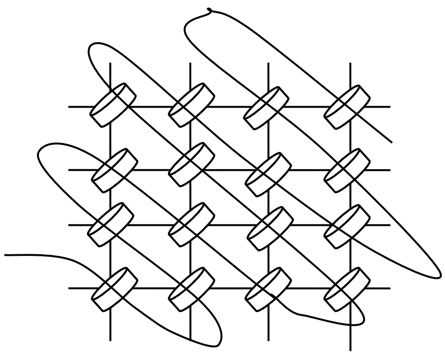


Figure (3)

Here the magnetic core consists of a ferrite core in the shape of a torrid ring as shown in figure.

We know that the ferrites have square hysteresis loop and low coercivity as shown in figure. Such hysteresis is used for making core memory as a different form of magnetic recording.

The magnetic cones of the memory are arranged in a matrix interlaced thought fine metal wires both horizontally and vertically as shown in figure (3)

A change in the state only occurs during reinforced magnetization i.e. both the horizontal current and vertical current pass through the core in same direction. The current passing through one of the wires will not induce a change in the magnetization of the cores reading of the magnetic cores is achieved using a third sense wire threaded through the core. It will pick up an induced voltage, if the core changes state. To facilitate a fast response for a high speed memory, soft magnets are always used in the core.

Giant Magneto Resistance effect

Principle

In hard disk drives, the binary data in terms of zero's (0) an one's (1) are stored by inducing magnetic moment in a thin magnetic layer and GMR effect is used as the principle to read the data in HDD. Here zero (0) represents missing transition and one (1) represents transition in the medium.

Construction

The HD consists of recording medium madeup of thin layer of magnetic garnets grown over the substrate. The GMR sensor, which is made up of ferrites and antiferromagnetic materials is used as reading element. The writing element is madeup of inductive magnetic transducer. The writing element and the GMR sensor shall be made to slide over the recording media in the longitudinal direction as shown in figure. Hence this method is also called as longitudinal recording. The flow of current through the GMR sensor and writing element shall be adjusted and in turn the magnetization is sensed (or) controlled in the recording media.

Working

Writing / Storing

1. Initially the current is passed through the writing element and a magnetic field is induced in between the gap of the inductive magnetic transducer.
2. During writing, the amplitude of current is kept constant, and the direction of current is reversed.

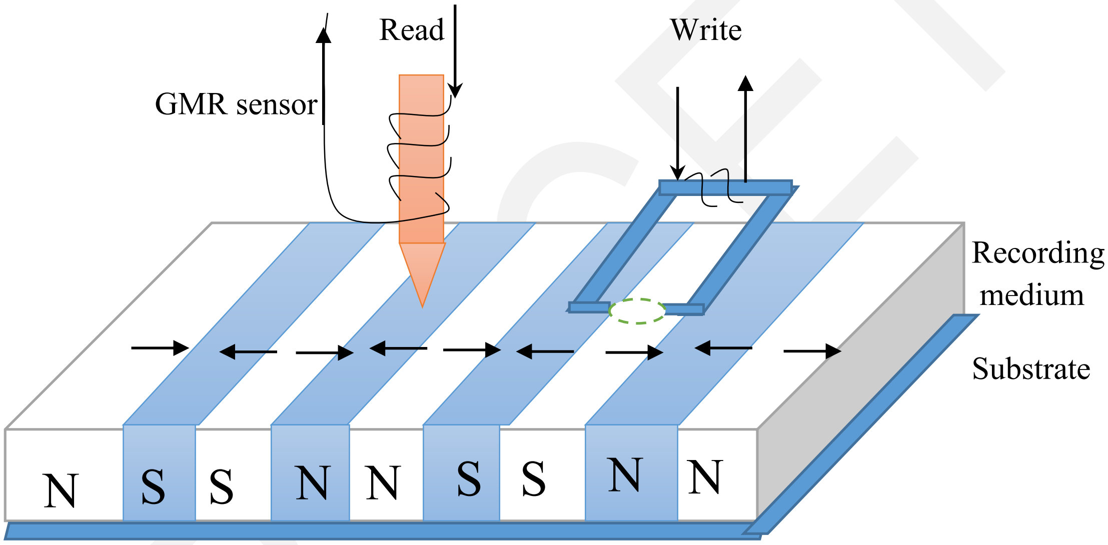
3. Due to reversal of current, the magnetization orientation is reversed in the recording medium i.e., from south → North as shown in figure

4. When the induced magnetic field is greater than the coercivity of the recording media, then data is recorded in the form of 1.

5. Thus one (1) is stored as data in the recording medium as a magnetic transition.

6. When there is no magnetic transition, then it is referred as zero (0).

7. In this way the zero's (0's) and one's (1's) are stored in the recording medium.



Reading / Retrieving

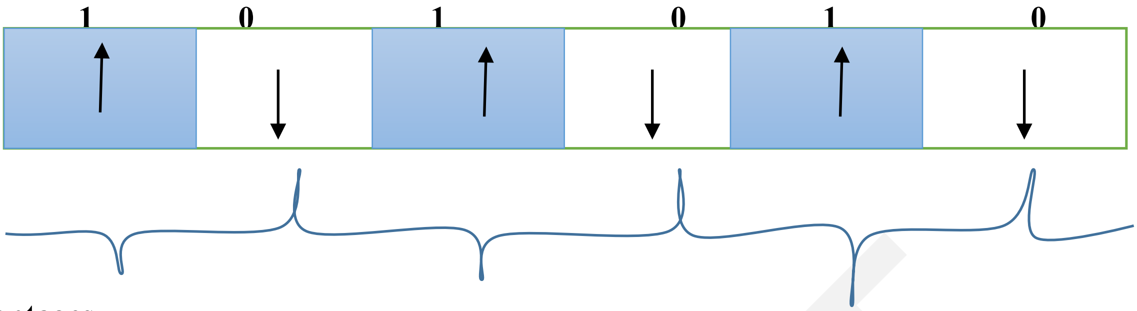
1. Giant Magnetoresistive (GMR) effect is the principle used to read / retrieve the data from the recording medium.

2. When the GMR sensor is made to move near the recorded medium, then the resistance of the GMR sensor varies with respect to the orientation of the magnetic moments as follows.

3. When the layers are magnetized in parallel manner, then the resistance in the GMR sensor is minimum and therefore maximum current flows through the sensor, which represents the data as one (1)

4. When the layers are magnetized in antiparallel manner, then the resistance in the GMR sensor is maximum and therefore minimum(or) almost no current flows through the sensor, which represents the data as zero (0)

5. Therefore with the help of the reading current, the zero's (0's) and one's (1's) can be retrieved from the magnetic hard disk drive.



Advantages

- HDD can store the data in terabytes
- It has very large storage capacity
- It is compact in size and can be easily transferred from one place to another.
- The size of recording medium is reduce up to few nano meter range using nanotechnology
- GMR sensor are non-diffusive and are very sensitive in reading

Disadvantages

- HDD is slower than soli state drives
- Consume large power
- Data may be corrupted due to thermal radiation
- HDD has bulkier form factor
- GMR noise ratio is high for nano size recording media

Applications

- Used as storage devices in cloud applications
- Used in coding and signal processing units
- Used in control systems, Nano electronics, etc.,

Questions and Answers

Part – A

1. What is Bohr magnetron?

When the atom is placed in a magnetic field, the orbital magnetic moment of the electron is quantized. A quantum of magnetic moment of an atomic system is known as Bohr magnetron.

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

2. **What is Curie constant & Curie law?**

Paramagnetic susceptibility $\chi = \frac{N\mu_0\mu_m^2}{3kT}$ (or) $\chi = \frac{C}{T}$ where N is the number of atoms per unit volume; μ_0 is the permeability of free space; μ_m – Induced dipole moment

Thus "*susceptibility of a paramagnetic substance varies inversely with the temperature"* is called Curie law and *C* is the curie constant.

3. **What is Curie – Weiss law?**

Ferromagnetic materials exhibit spontaneous magnetization below a temperature called the curie temperature and above it becomes paramagnetic and obeys Curie Weiss law given by

Susceptibility $\chi = \frac{C}{T-\theta}$. Where *C* – Curie constant & θ – paramagnetic Curie temperature.

4. **What is domain theory of ferromagnetism?**

According to Weiss, a ferromagnetic specimen consists of large number of small regions called domains which are spontaneously magnetized due to the parallel alignment of all magnetic diploes. The direction of spontaneous magnetization varies from domain to domain.

5. What are energies involved in origin of domains in ferromagnetic material?

Magnetostatic energy, Crystalline (or) anisotropic energy, Domain wall energy, Magnetostriction energy.

6. On the basis of spin how the materials are classified as dia, para, ferro, antiferro & ferri magnetic?

- Materials which does not possess any permanent dipole moment are known as diamagnetic materials
- If the permanent dipole do not interact among themselves and are align in random direction, then those materials are paramagnetic.
- If the permanent dipole are strong and align themselves in parallel, then those materials are called diamagnetic.
- If the permanent dipole are strong and align themselves antiparallel with equal magnitude, then those materials are called antiferromagnetic
- If the permanent dipole are strong and align themselves antiparallel with unequal magnitude, then those materials are called ferrimagnetic.

7. What is ferromagnetism?

Certain materials like iron, cobalt, nickel and certain alloys exhibit spontaneous magnetization. i.e., they have amount of magnetization (atomic moments are aligned) even in the absence of an external magnetic field. This phenomenon is called ferromagnetism.

8. Give the properties of diamagnetic materials.

- Permanent dipoles are absent. Therefore the magnetic effects are very small
- When placed inside the magnetic field, magnetic lines of forces are repelled
- The magnetic material have negative susceptibility
- Magnetic susceptibility is independent of applied field strength and temperature
- Relative permeability is slightly less than unity
- Example: Gold, Bismuth and Organic materials

9. **Give the properties of paramagnetic materials?**

- It possess permanent magnetic dipoles
- When placed inside the magnetic field, it attracts the magnetic lines are forces
- In the absence of the magnetic field, the dipoles are randomly oriented. There is a small amount of magnetic moment in the absence of external field.
- When magnetic field is applied, magnetic moment along the field direction increases with increasing magnetic induction.
- Paramagnetic susceptibility is positive and greatly depends on temperature.
- Paramagnetic susceptibility is independent of applied field strength.
- When the temperature is less than Curie temperature it becomes diamagnetic.

10. **What are the properties of ferro magnetic materials?**

- It exhibits magnetization even in the absence of external field
- This materials exists as ferro magnetic when temperature is below ferromagnetic curie temperature and become paramagnetic above ferromagnetic curie temperature
- It consists of number of small spontaneously magnetized region called domains
- During heating they loss their magnetization slowly
- Spin alignment are parallel in same direction
- They attracts magnetic lines of forces strongly
- Susceptibility is very large & positive

11. **What are the properties of ferri magnetic materials?**

- It possess net magnetic moment
- Magnetic susceptibility is very large & positive. It is given by $\chi = \frac{C}{T \pm \theta_N}$

Where θ_N- Neel Temperature.

- Spin alignment is antiparallel of different magnitude
- The susceptibility is graphically temperature dependent.

12. **What are soft magnetic materials?**

Materials which are easy to magnetize and demagnetize are called soft magnetic materials

13. **State the properties of soft magnetic materials?**

- They have high permeability
- They have low coercive force.
- They have low hysteresis loss.

14. **What are the essential differences between hard and soft magnetic materials?**

S.No	Hard magnetic materials	Soft Magnetic Materials
1.	They have large hysteresis loss	They have small hysteresis loss
2.	The eddy current loss is high	Eddy current loss is low
3.	They have small values of permeability & Susceptibility	They have large values of permeability & Susceptibility
4.	Domain wall movement is difficult& irreversible in nature	Domain wall moves easily& reversibly
5.	The coercivity & retentivity are large	The coercivity & retentivity are small
6.	Eg: Carbon steel, Tungsten Steel, Chromium Steel.	Eg: Iron, Ferrites, Silicon Alloys

15. Define Susceptibility?

The ratio of the intensity of magnetization produced in the sample (I) to the magnetic field intensity which produces the magnetization (H). i.e., $\chi = \frac{I}{H}$

16. State few applications of soft magnetic materials

- Cast iron is used in the structure of electrical machinery and frame work of DC machine
- Carbon steel has high mechanical strength used in making motor of turbo alternators.

17. What are hard magnetic materials?

Materials that retain their magnetization and are difficult to demagnetize are called hard magnetic materials.

18. State the properties of hard magnetic materials

- They possess high retentivity
- They possess high value of B-H product
- They have high coercivity
- They have low permeability

19. Mention few applications of hard magnetic materials.

- Tungsten steel is used in making permanent magnets for dynamos, motor.
- Cobalt steel is sued in motor, fans and heavy duty instruments.

20. What is antiferromagnetism?

Any materials having the magnetic interaction between any two dipoles align themselves antiparallel to eachother are called antiferromagnetic materials.

21. What are Ferrites and mention its types?

Ferrites are modified structure of iron with no carbon atoms in which the adjacent magnetic moment are of unequal magnitudes aligned in antiparallel direction.

General Formula: $X^{2+} Fe^{3+}O_4^{2-}$

Types: Regular Spinal, Inverse Spinal

22. **State the applications of ferrites?**

- They are used in transformer cores for high frequencies up to microwaves.
- They are used in radio receivers to increase the sensitivity and selectivity of the receiver
- They are used in digital computers and data processing circuits
- They are used in power limiting and harmonic generation devices

23. What is ferrite core memory?

It is the memory made up of a ferrite core in the form of rings used for random storage of data '0' & '1' by magnetizing the ring in any of the two opposite direction.

24. **Define Hysteresis?**

When the ferromagnetic material undergo a cycle of magnetization, the intensity of magnetization (I) & magnetic flux density (B) lags behind the applied magnetic field strength (H) & this process is called Hysteresis.

25. What is the principle of magnetic recording system?

It states the data in the form of magnetization pattern as a sequence of binary magnetization states in the magnetic medium because the ferromagnetic material produces the magnetic dipoles align themselves parallel to each other.

26. What are the advantages and disadvantages of magnetic discs?

Advantage:

- It has very large storage capacity
- Thousands of files can be permanently stored
- Very high speed in writing & reading the information
- Prevented from dust particles, because it is sealed

Disadvantage:

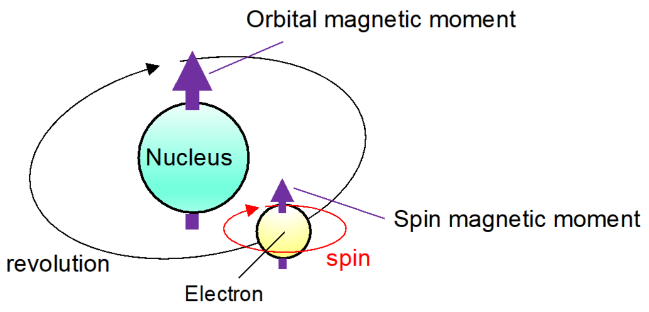
- It is very costly
- If data is once corrupted, there is a heavy loss of data

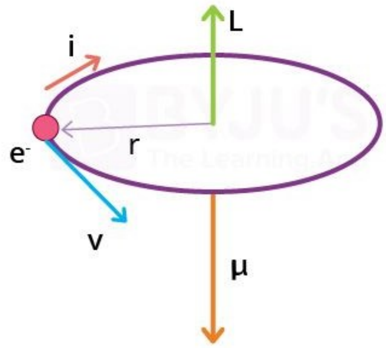
Part – B Question and Answers

1. Explain the origin of atomic magnetic moments.

The fundamental reason for the response of a material to an external magnetic field is that the atoms possess magnetic moments. That is, each atom acts like a tiny magnet. There are two source that contribute to atomic magnetic moment.
(i) Magnetic moment due to the movement of electrons in orbits around the nucleus, i.e., due to orbital angular momentum. This is called the orbital magnetic moment.
(ii) Magnetic moment due to spin of the electrons, i.e., due to spin angular momentum . This is called spin magnetic moment.
(iii) in addition to the above two contribution, there is a small contribution due to spin angular momentum of the nucleus called the nuclear magnetic moment. But the nuclear magnetic moments are very much smaller and so their interaction of the electronic magnetic moment.

Magnetic moment due to orbital angular momentum of electrons.
The orbital motion of electron revolving about a nucleus is equivalent to a tiny current loop. This produces a magnetic moment perpendicular to the plane of the orbit as shown in figure.





Derivation

<u>Orbital angular momentum of the electrons:-</u> μ_0

Consider an electron revolving in an orbit with radius 'r' moving with linear velocity 'v' and produces a constant angular velocity 'ω'. Let T be time taken for one revolution and 'e' be the magnitude of charge on the electron.

The current across any point in the orbit is $I = \frac{\text{Charge of electron (-e)}}{\text{Time (T)}}$ (1)

But $T = \frac{2\pi}{\omega}$ (2)

Any electron revolving around orbit produces magnetic field perpendicular to its plane which produces an orbital magnetic moment given by

$$\mu_0 = IA \quad (3)$$

$$= \left(\frac{e\omega}{2\pi}\right)\pi r^2$$

But v = rω and $\omega = \frac{v}{r}$ (4)

$$\therefore \mu_0 = \left(\frac{evr}{2}\right)$$

$$= -e\left(\frac{mvr}{2m}\right) \qquad \mu_0 = \left(\frac{-eL}{2m}\right) \quad (5)$$

where L = m v r

Equation (5) represents the expression for the magnetic moment associated with the orbital motion of the electron.

The negative sign indicates that the orbital magnetic moment and angular momentum lie in opposite direction.

Bohr magneton

The magnetic moment contributed by an electron with angular momentum quantum number n = 1 is known as Bohr magneton.

We know that $\mu_0 = \left(\frac{-eL}{2m}\right)$

According to quantum theory, orbital angular momentum is $L = n\hbar$

(or) $L = \frac{nh}{2\pi}$ since $\hbar$ [illegible] and n is the orbital angular momentum quantum number.

Substituting the above values and considering the electrons in ground state ($n = 1$)

The magnetic moment in terms of Bohr magneton is given by $\mu_B = \left(\frac{eh}{4\pi m}\right)$

By substituting the values of h, m in the above equation, we get Bohr magnetron given by $\mu_B = 9.27 \times 10^{-24}$ Am^2

Electron spin magnetic moment (μ_S)

In an atom, every two electrons will form a pair with opposite spins. Thus the resultant spin magnetic moment is zero. But in magnetic materials, the unpaired electrons spin magnetic moments interacts with the adjacent atom's to form unpaired electron spin magnetic moment which is responsible for ferro and paramagnetic behaviour of materials. Accordingly to Quantum theory, spin magnetic moment $\mu_S = \frac{e}{m}\mathbf{S}$

Where $\mu_S = \pm 1$ Bohr Magnetron.

Nuclear spin magnetic moment (μ_N)

The mass of the nucleus is larger than that of electron by a factor of the order of 10^3. Hence, nuclear spin magnetic moment is of the order of 10^{-3} Bohr magnetron.

Since μ_S and μ_N are very small, then the practical purpose, the total magnetic moment arises due to spin magnetic moment.

2. Explain the domain theory of ferromagnetism. Using that explain the phenomenon of Hysteresis in ferromagnetic materials.

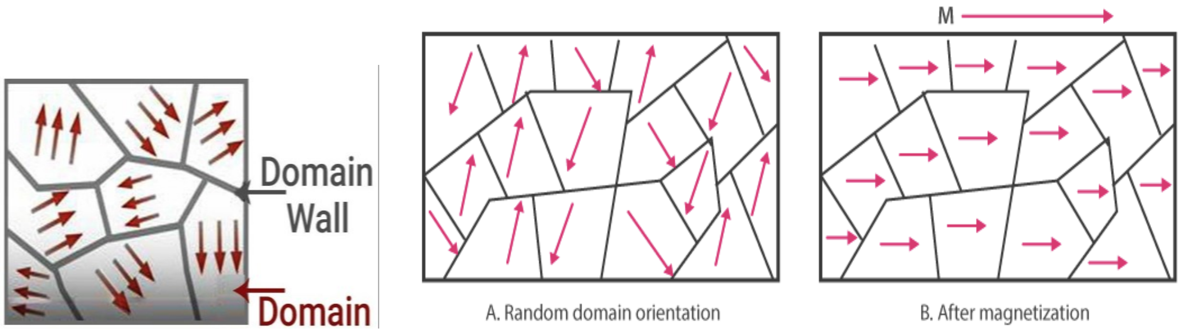
Weiss proposed the concept of domains in order to explain the properties of ferromagnetic materials.

Principle

The group of atomic dipoles (atoms with permanent magnetic moment) organised in tiny bounded region in the ferromagnetic materials are called magnetic domains.

Explanation

Ferromagnetic materials contains a large number of domains. In each domain, the magnetic moments of the atoms are aligned in same direction. Thus, the domain is a region of the ferromagnetic material in which all the magnetic moments are aligned to produce a net magnetic moment in one direction only.



Thus, it behaves like a magnet with its own magnetic moment and axis. In a demagnetized ferromagnetic material, the domains are randomly oriented as shown in figure. So that the magnetization of the material as a whole is zero. The boundaries separating the domains are called *domain walls*. These domain walls are analogous to the grain boundaries in a polycrystalline material.

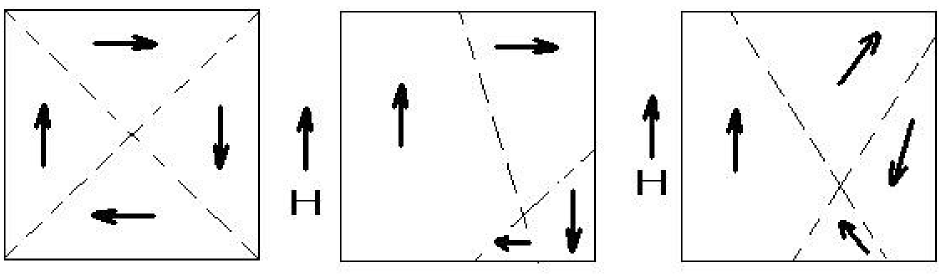
However, the domain walls are thicker than the grain boundaries. Like grain growth, *the domain size* can also grow due to the movement of domain walls. When a magnetic field is applied externally to a ferromagnetic material, the domains align themselves with field as shown in figure. This results in a large net magnetization of the material.

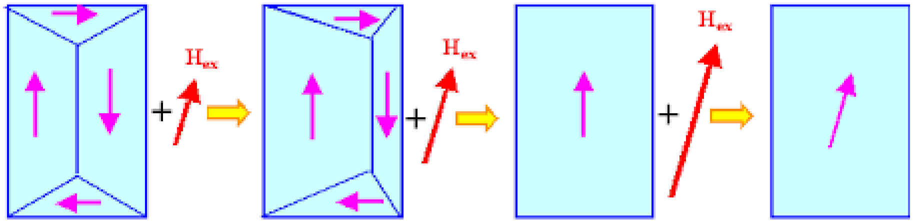
Process of domain magnetization

We know that in an unmagnetized specimen, the domains are randomly oriented and the net magnetization is zero. When the external magnetic field is applied, domains align with the direction of field resulting in large net magnetization of a material. There are two possible ways in which the domains are aligned in the external field direction.

(a) By the motion of domain walls

Figure (a) shows an unmagnetized specimen in which domains are randomly aligned. When a small magnetic field is applied, the domains with magnetization direction parallel or nearly parallel to the field, grow at the expense of others as shown in figure (b). This domain growth occurs due to the movement of domain walls away from the minimum energy state.





(b) By rotation of domains

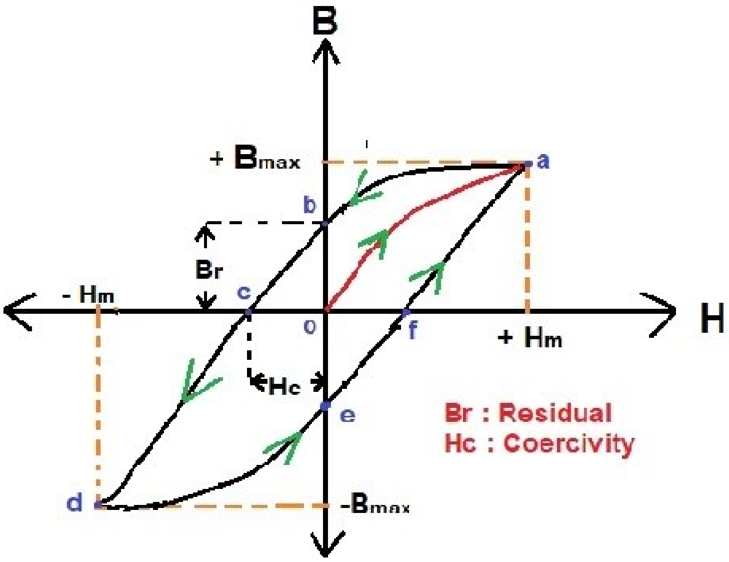
As the magnetic field is increased to a large value (i.e., near saturation) further domain growth becomes impossible through domain wall movement. Therefore, most favourably oriented and fully grown domains tends to rotate so as to be in complete alignment with the field direction as shown in figure.

Origin of domains

We know that according to thermodynamics, the free energy of a solid tends to reach a minimum. It is found that the domain structure occurs in order to minimise the total energy of ferromagnetic solid.

Hysteresis M – H Behaviour of Ferromagnetic materials

A graph is drawn by plotted magnetic field strength 'H' along X-axis and magnetic induction 'B' along Y-axis as shown in fig below.



- ❖ 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 magnetization.(**Saturation Magnetization - B_{sat}**)
- ❖ The value of magnetic field is decreased, but the magnetic induction does not decrease at the same rate at which it is increased. When H=0, $B \neq 0$, the magnetic induction has a definite value represented by OB and it is known as **retentivity**.

- 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 it is known as **coercivity**.
- 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 magnetization. The loop ABCDEFA 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 magnetizing field. It is represented by OB in the B-H curve (fig)

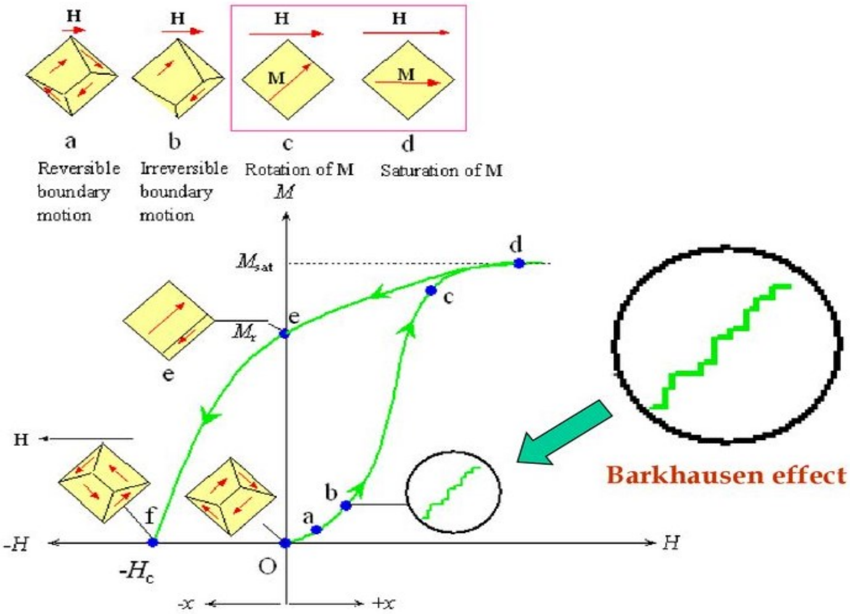
Coercivity or Coercive force

Coercivity or coercive force is the amount of magnetizing 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)

Hysteresis loss

When a specimen is taken through a cycle of magnetization, then 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. What are reversible and irreversible domains? Based on that explain the phenomenon of hysteresis in ferromagnetic materials.



When a Ferromagnetic is subjected to external field, there is an increase in the value of the resultant magnetic moment due to

(i) The movement of domain walls
(ii) The rotation of domains

When a weak external field is applied, the domain walls are displaced slightly in the soft direction of magnetization. This gives rise to small magnetization corresponding to the initial portion of the hysteresis curve (OA) as shown in figure .Now, if applied field is removed, then the domains return to its original state and it is known as "**Reversible Domains**".

When a strong external field is applied, large number of domains contributes to the magnetization and thus the magnetization increases rapidly with "H"↑

Here, 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 Figure and this domains are called **"Irreversible Domains".**

At point "B" all the domains have got magnetized along the soft direction. Now, when the field is further increased, the domains start rotating along with the field direction and the anisotropic energy is stored in the "*Hard Direction*" represented as "BC" in figure

Thus the specimen is said to attain the maximum magnetization 'M_s'. At this position, even after the removal of external field the material possess residual magnetization called **"Retentivity"** represented by "OE" in figure

Actually after 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 spend to reduce the magnetization to zero is called **"Coercivity"** represented by "OF" in figure

Hysteresis Loss:

It is the loss of energy in taking a ferromagnetic specimen through a complete cycle of magnetization and the area enclosed is called "Hysteresis Loop". Based on this area of hysteresis, the magnetic are classified as soft and hard magnetic materials.

4. What are the different types of energies involved in domain theory of ferromagnetism?

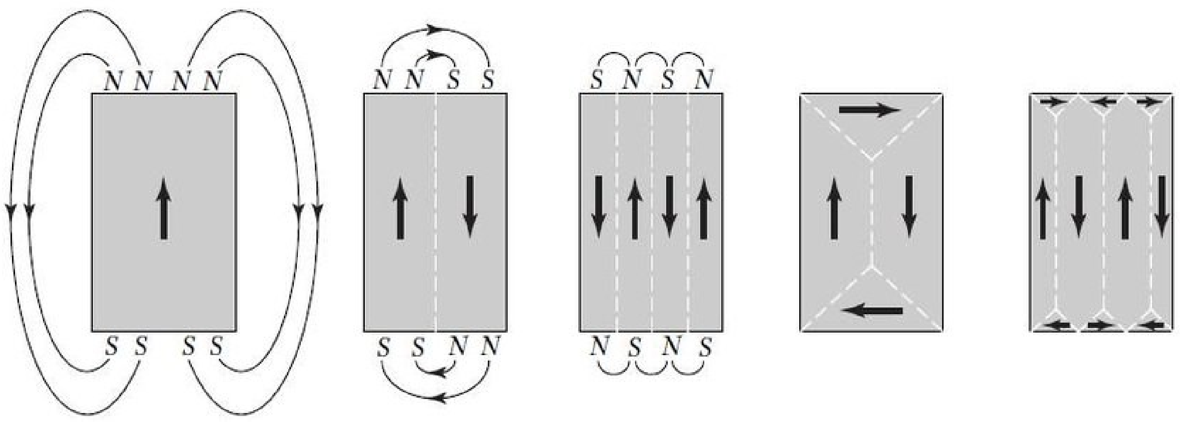
To study the domain structure clearly, we must know four types of energy involved in the process of domain growth. They are:

(1) Exchange energy **(2) Magnetostatic energy**

(3) Crystal anisotropy energy **(4) Magnetostrictive energy**

Exchange energy

It is energy associated with the quantum mechanical coupling that aligns the individual atomic dipoles within a single domain. It arises from interaction of electron spins. It depends upon the interatomic distance. Figure (a) shows a cross section through ferromagnetic crystal having a single domain structure established by exchange energy with a saturation.



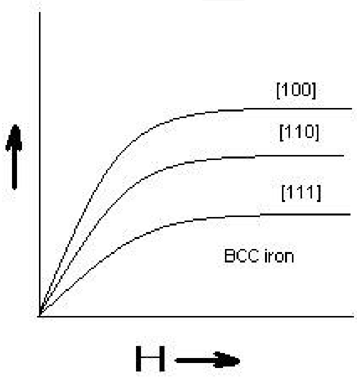
(a) (b) (c) (d) (e)

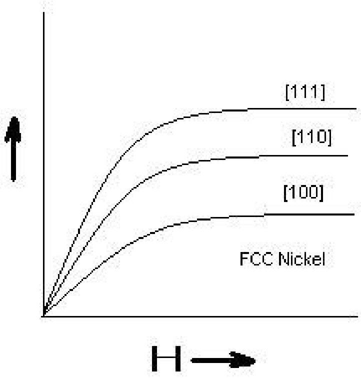
Magnetostatic energy

Magnetostatic energy or magnetic potential energy is the energy present in any ferromagnetic material when the material produces an external field. The magnetic energy of the specimen can be reduced by dividing the single domain into two domains as shown in figure (b). Further, subdivision into N domains (figure c) reduces the magnetic energy to 1/N of the magnetic energy of the material with single domain.

Crystal anisotropy energy

It is the energy of magnetization which is the function of crystal orientation. In the below figure magnetization curves for iron with applied field along different crystallographic direction and different crystal structure are shown (BCC & FCC)



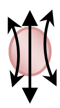
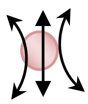


From the figure, it is clear that, BCC iron require much greater fields to produce magnetic saturation in [111] direction as compared to the field required in [100] direction. Here the difference in magnetic energy to produce magnetic saturation in an easy [100] direction and [111] direction is called *crystal anisotropic energy*.

Magnetostrictive energy

When a material is magnetised, it is found that it suffers a change in dimensions. This phenomenon is known as magnetostriction. This deformation is different along different crystal direction. So if the domains are magnetised 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.

5. Distinguish briefly about diamagnetic material, paramagnetic material and ferromagnetic material?

	Diamagnetic material	**Paramagnetic material**	**Ferromagnetic material**
Definition	The material with no permanent dipole moment. The external field decreases the magnetic induction present in the specimen	The material with permanent dipole moment but do not interact among themselves. The external magnetic field increases the magnetic induction present in the specimen	The material with strong permanent dipole moment and interact among themselves. The external field increases a large magnetic induction in the specimen.
Susceptibility and its temperature dependence	It is negative and independent of temperature and applied magnetic field.	It is always positive and small and it is inversely proportional to absolute temperature of material	It is always positive and large and depends on temperature in complex manners.
Behaviour of material in magnetic field	The magnetic lines of forces are repelled away from the material. Bout > Bin 	The magnetic lines of forces are attracted towards the centre of material. Bin > Bout 	The magnetic lines of forces are highly attracted towards the centre of material. Bin >> Bout 
Spin on magnetic moment alignment	No spin (or) magnetic moment	All spins (or) magnetic moments are randomly oriented	All spins (or) magnetic moments are orderly oriented.

Origin	Arises from lamer precession	Arises from the magnetic moments orientation	Arises from spontaneous magnetization due to total molecular magnetic field.
Magnetic phase transition	At low temperature, super conductor are diamagnetic when temperature increases it becomes conductor.	When temperature is less than curie temperature. It is diamagnetic. But paramagnetic curie temperature is low.	When temperature is higher than curie temperature it is paramagnetic. But in ferromagnetic curie temperature is high.
Examples	Hydrogen, Bismuth	Aluminum, Platinum	Iron, Nickel and Cobalt.

6. Distinguish between soft and hard magnetic materials.

Magnetic materials are classified in to two types based on magnetization
(i) Soft magnetic materials (ii) Hard magnetic materials

Soft magnetic materials

Definition

Materials which are easy to magnetize and demagnetize are called soft magnetic materials. These magnetic materials do not retain the alignment of magnetic domains after the removal of the external magnetic field.

Properties

- The soft magnetic materials can be magnetised and demagnetised easily.
- They have high permeability
- They have low residual magnetism
- They exhibit low hysteresis loss
- They have low hysteresis loss
- The magnetic energy stored is low

Examples:

- Pure or ingot iron
- Cast iron (carbon above 2.5%)
- Carbon steel
- Silicon steel
- Manganese and nickel steel
- Permalloy (Ni: Fe alloy = 78.15% : 21% + small quantities of Cr, Co, Cu and Mn)
- Mumetal (Ni =75.4%, Cu-4%, Cr-1.5% and remaining Fe)
- Perminar (Co-Ni-Fe alloy = 50%, 25%, 25%)
- Soft ferrites

Applications

- Cast iron is sued in the structure of electricity machinery and the frame work of DC machine
- Carbon steel has high mechanical strength and it is used in making motor of turbo alternators
- Silicon steel is used for the construction of poles of motor and dynamo and core plates of transformer
- Manganese and nickel steel is used for making cable boxes, meter cases and end rings of turbo alternators
- Permalloy is used as thin tape wrapped around the conductors of loaded submarine cables.
- Mumetal is used for making cores of transformers.
- Perminar is used in armatures of motors, transformer cores, etc.,

Hard magnetic materials

Definition

Materials which retain their magnetism and are difficult to demagnetize are called hard magnetic materials. These magnetic materials retain the alignment of the magnetic domains permanently even after the removal of external magnetic field

Properties

- The hard magnetic materials have low permeability and strongly repel the magnetic field
- They have high retentivity and coercivity
- They require high magnetising force to attain magnetic saturation
- They have large hysteresis loop area and large energy loss.
- The value of B – H product is high.

Examples

- **Tungsten steel**: it contains 4.5 to 6% tungsten, o.5 to 0.7% carbon and the remaining is iron.
- **Carbon steel**: It contains 34% cobalt, 5% chromium, 3.5 to 6% tungsten and remaining is iron.
- **Alini:** it contains 10 – 15% aluminium, 25-30% nickel and 65-75% iron.
- **Alinco**: It contains 18% nickel, 10% aluminium, 5% copper, 15% cobalt and remaining is iron.
- **Cunife**: It contains 50% copper, 30% nickel and 20% iron
- **Hypernic**: It contains 50% of nickel and 50% of iron.

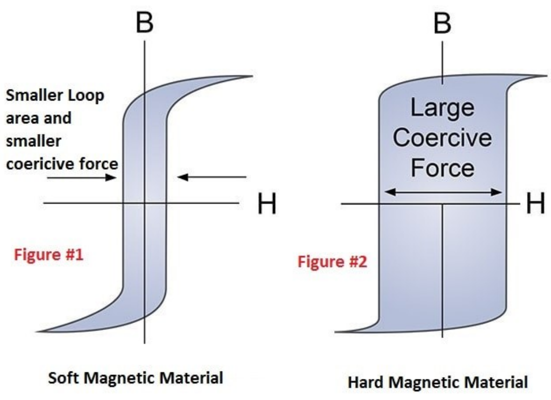
Applications

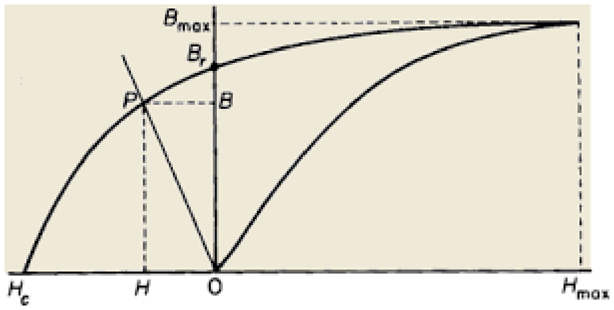
- Tungsten steel is used in making permanent magnets for dynamos and motors.
- Cobalt steel is used in motors, fans and heavy duty instruments.

- Alini is used in the design of portable and light weight instruments
- Alnico is used for the production of permanent magnets in smaller size
- Cunife is useful in producing small size magnets.

Energy product

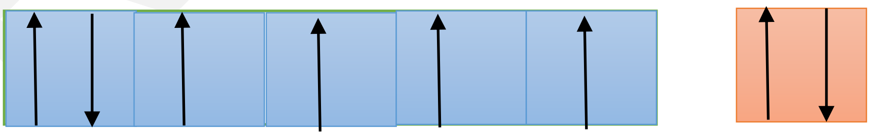
The product of retentivity (B_r) and coercivity (H_c) is known as energy product. It represents the maximum amount of energy stored in the specimen. Therefore, for permanent magnets the value of energy product should be very high as shown in figure.





7. Discuss the origin of ferromagnetism and exchange interaction

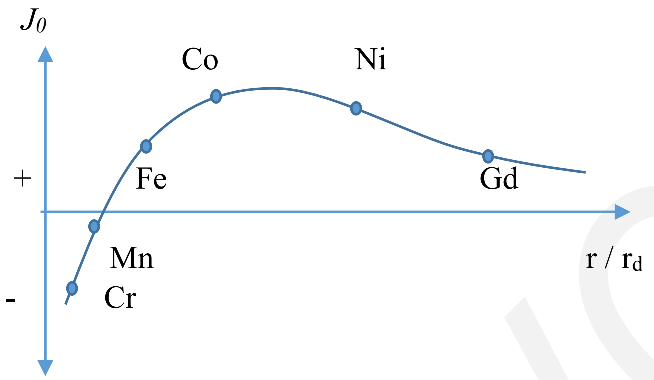
The ferromagnetic property is exhibited by transition elements such as iron, cobalt and nickel at room temperature and rare earth elements like gadolinium and dysprosium.
The ferromagnetic materials possess parallel alignment of dipoles. This parallel alignment of dipoles is not due to the magnetic force existing between any two dipoles. The reason is that the magnetic potential energy is very small and it is smaller than thermal energy.
The electronic configuration of iron is $1s^2$, $2s^2$, $2p^6$, $3s^2$, $3p^6$, $3d^6$, $4s^2$. For iron , the $3d$ sub shell is an unfilled one. This $3d$ subshell have five orbitals. For iron, the six electron present in the $3d$ subshell occupy the orbitals such that there are four unpaired electrons and two paired electrons as shown in figure.



These four unpaired electrons contribute a magnetic moment of $4\mu B$. This arrangement shows the parallel alignment of four unpaired electrons. The parallel alignment of dipoles in iron is not due to the magnetic interaction. It is due to the Pauli's exclusion principle and electrostatic interaction energy. **The Pauli's exclusion principle and electrostatic interaction energy are combined together and constitute a new kind of interaction known as exchange interaction. The exchange interaction is a quantum mechanical concept.** The exchange interaction between any two atoms depends upon the interatomic separation between the two interacting atoms and the relative spins of the two outer electrons. The exchange interaction between any atoms is given by $E_{ex} = -J_e S_1 S_2$

Where J_e is the numerical value of the exchange integral, S_1 *and* S_2 are the spin angular momenta of the first and second electrons. The exchange integral value is negative for the number of elements. Therefore, the exchange energy value is negative when the spin angular momentum S_1 *and* S_2 are opposite direction. Hence antiparallel alignment of diploe is favoured. This explains the antiparallel alignment of dipoles in antiferromagnetic materials.

In some materials like iron, cobalt and nickel the exchange integral value is positive. The exchange energy is negative when the spin angular momentum is in the same direction. This will produce a parallel alignment of dipoles. A plot between the exchange integral and the ratio of the interatomic separation of the radius of 3*d* orbital (r/r_d) is shown in figure.



For the transition metals like iron, cobalt, nickel and gadolinium the exchange integral is positive, whereas for manganese and chromium the exchange integral is negative. The positive value of the exchange integral represents the material is ferromagnetic and the negative exchange integral value represents the material us antiferromagnetic. In general, if the ratio, $r/r_d > 3$, the material is ferromagnetic, otherwise it is antiferromagnetic.

8. Explain in detail about antiferromagnetism and ferrimagnetism.

Antiferromagnetism

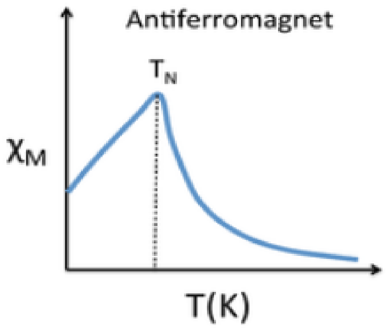
Antiferromagnetic materials are magnetic materials which exhibit a small positive susceptibility of the order of 10^{-3} to 10^{-5}. The variation of susceptibility with temperature shows a peculiar pattern in these materials. The susceptibility increases with increasing temperature and it reaches a maximum at a certain temperature called Neel temperature T_N. With further increase in temperature, the material reaches paramagnetic state. The material is antiferromagnetic below T_N. The transition temperature T_N lies far below the room temperature for most of the materials.

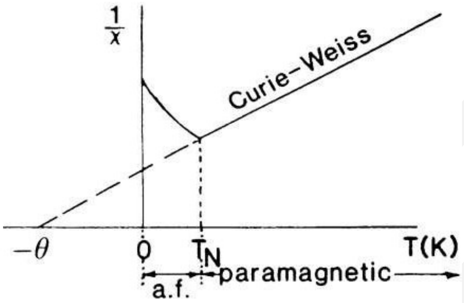
In the paramagnetic state, the variation of inverse susceptibility ($1/\chi$) with temperature is linear as shown in figure. The extrapolation of the paramagnetic line in figure to $1/\chi = 0$ yields a negative θ. Therefore, the variation of susceptibility with temperature obeys modified Curie-Weiss law.

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

Where θ – paramagnetic Curie temperature; C – Curie's constant.

In antiferromagnetism, the magnetic moments of sublattices in unit cell are equal in magnitude but opposite in direction, so they cancel out each other. This gives net zero magnetization.



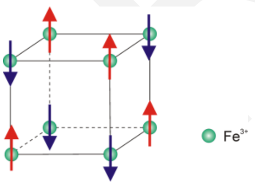


Definition

Any materials having the magnetic interaction between any two dipoles align themselves antiparallel to eachother are called antiferromagnetic materials.

Properties

- The adjacent dipoles align antiparallel and hence the net magnetic moment is zero
- The antiparallel alignment of adjacent dipoles is due to exchange interaction between them
- The magnitude of susceptibility is small an positive
- The susceptibility (χ) increases with increase in temperature up to Neel temperature (θ_N), Beyond the Neel temperature, the susceptibility decreases with temperature
- In antiferromagnetic materials, Neel temperature (θ_N) is the temperature at which susceptibility of the material is maximum.
- Example: Ferrous oxide, Manganese oxide and chromium oxide.



Ferrimagnetism

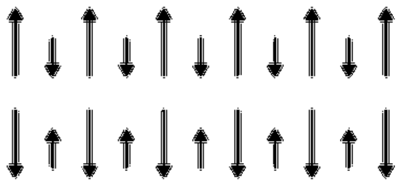
There are some magnetic materials in which the magnetic moments of two sub lattices are opposite in direction but not exactly equal in magnitude (because of two different types of ions in the lattices). Such crystals possess spontaneous magnetization and exhibit most of the properties of ferromagnetic materials. This uncompensated antiferromagnetism is known as ferrimagnetism.

Ferrimagnetic materials (or) ferrites

Substance which possess a spontaneous magnetization in which the magnetic moments of the two sub lattice are opposite in direction but not exactly equal in magnitude are called "Ferrites".

Properties

- Ferrites has net magnetic moment
- Above Curie temperature, it becomes paramagnetic and it behaves as ferrimagnetic material below Curie temperature.
- The susceptibility of ferrite is very large and positive. It depends on temperature. It is given by $\chi_{ferri} = \frac{C}{T \pm \theta}$ for $T > T_N$.
- Spin alignment is antiparallel of different magnitudes as shown in figure.



- Mechanically, it has pure iron character.
- They have high permeability and high resistivity
- They have low eddy current loss and low hysteresis loss.

Applications

- Hard magnetic ferrites are used in the manufacture of permanent magnets
- Such magnets are used in super high frequency technology.
- Soft magnetic ferrites are used in the production of cores for inductor coils used in telecommunication and low power transformers.
- Ferrites are used in magnetic flims in which demagnetization process occurs at the speed exceeding million times/second. This technology is important for electronics, automobiles and computer hardware engineering.
- Ferrites re used in information storage devices such as magnetic discs and tapes.
- Ferrite rods are used to produce ultrasonics by magnetostriction principle.
- Ferrite rods are used in radio receiver to increase sensitivity and selectivity.
- Since the ferrite has low hysteresis loss and eddy current loss, it is used in two port m microwave devices such as gyrator, circulator and isolator.

9. Explain magnetic principle in data storage mechanism.

In general memory units are the devices used to store the information in the form of bits. [8 bit =1 byte]. The memory units are classified as (i) Main memory (or) internal memory (ii) Auxiliary memory (or) External memory

Main Memory:

The memory unit of CPU is called main memory. Thus data's are write and finally be erased if necessary. Eg: EPROM, ROM, RAM etc.,

Auxiliary Memory:

This type of memory is also referred to as back-up storages because; it is used to store large volume of data on permanent basis. This date can be accessed or recopied if necessary. Eg: Magnetic tapes, Magnetic disk, Ferrite core memories and Bubble memories.

1. Magnetic Tape:

The tape is a plastic ribbon with metal oxide material coated on one side which can be magnetized, in this information can be written and also can be read by write/read heads. Information recorded in the tape is in the form of tiny magnetized and non-magnetized spots on the metal oxide coating. The magnetized spot represents '1' sun magnetized spot represent '0' in binary code. The information can be accessed, processed, erased and can be stored again in same area.

Advantages:-

- Storage capacity is large, Easy to handle
- Loss expensive, Erased and reused.

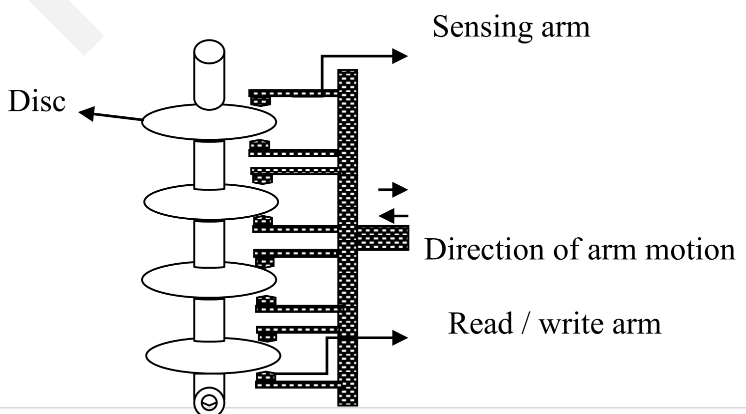
Disadvantages:-

- It consumes lot of time.

2. Magnetic Disc Devices:

(A) Hard disk drives:

It is the direct access storage device made up of hard aluminum platters. This platter surface is carefully machined for flat. This surface is coated with magnetic oxides and built in to a bar. Similar such disks are mounted on a vertical shaft, forming a disk pack as shown in figure. The drive mechanism drives the disc pack with the spindle. The data is written can read by the R/W heads in the horizontal sensing arms by moving in and out between the platters with the precaution that the R/W head doesn't touches the surface instead, it fly over the disk surface by a fraction of a mm.



Advantages:-

- It has large storage capacity.
- Thousand of files can be permanently stored.
- Very high speed in reading and writing the information
- This is prevented from dust, since they are sealed.

Disadvantages:-

- It is very costly
- If data is completed, there is a heavy loss.

(*B) Floppy disc drives*:

Floppy is made of a very thin and flexible plastic materials coated with magnetic materials. This disc is inserted in floppy disc drive for read/write operation by the read/write head in the disc. Size: 5.25" called mini floppy, 3.25" called micro floppy.

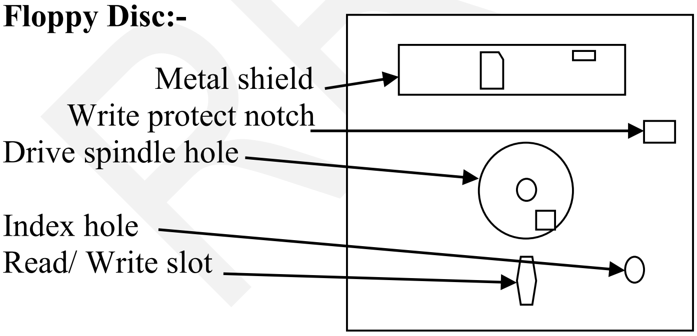
Organization:-

Surface of the floppy disc is divided into a number of concentric circles known as tracks where the information is recorded. The tiny magnetic spots are used to record the logic 1 (or) 0 state. The spot magnetized in one direction are '1' state and in other direction are called '0' state. Each track has number of sectors

Operation;-

When the floppy is put in drive unit. When drive is operated. The floppy disc is rotated which makes physical contact with read/write head. This magnetic material movement is controlled by serve mechanism.

Floppy Disc:-



Advantages:-

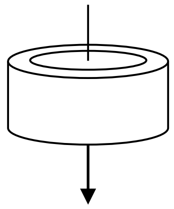
(iv) Storing and transporting of data is easier.
(v) Cost is less
(vi) It can reused many times

Disadvantages:-

(i) Storage capacity is less

(ii) Care to be taken for handling.

3. <u>Ferrite Core Memory:</u>



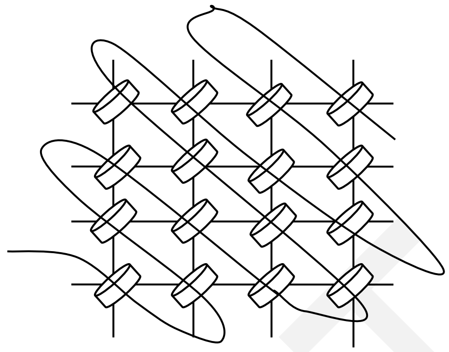


Figure (3)

Here the magnetic core consists of a ferrite core in the shape of a torrid ring as shown in figure. We know that the ferrites have square hysteresis loop and low coercivity as shown in figure. Such hysteresis is used for making core memory as a different form of magnetic recording.

The magnetic cones of the memory are arranged in a matrix interlaced thought fine metal wires both horizontally and vertically as shown in figure (3). A change in the state only occurs during reinforced magnetization i.e. both the horizontal current and vertical current pass through the core in same direction. The current passing through one of the wires will not induce a change in the magnetization of the cores reading of the magnetic cores is achieved using a third sense wire threaded through the core. It will pick up an induced voltage, if the core changes state. To facilitate a fast response for a high speed memory, soft magnets are always used in the core.

10. Describe the working of magnetic hard disc based on Giant Magneto Resistance sensor (GMR).

Principle

In hard disk drives, the binary data in terms of zero's (0) an one's (1) are stored by inducing magnetic moment in a thin magnetic layer and GMR effect is used as the principle to read the data in HDD. Here zero (0) represents missing transition and one (1) represents transition in the medium.

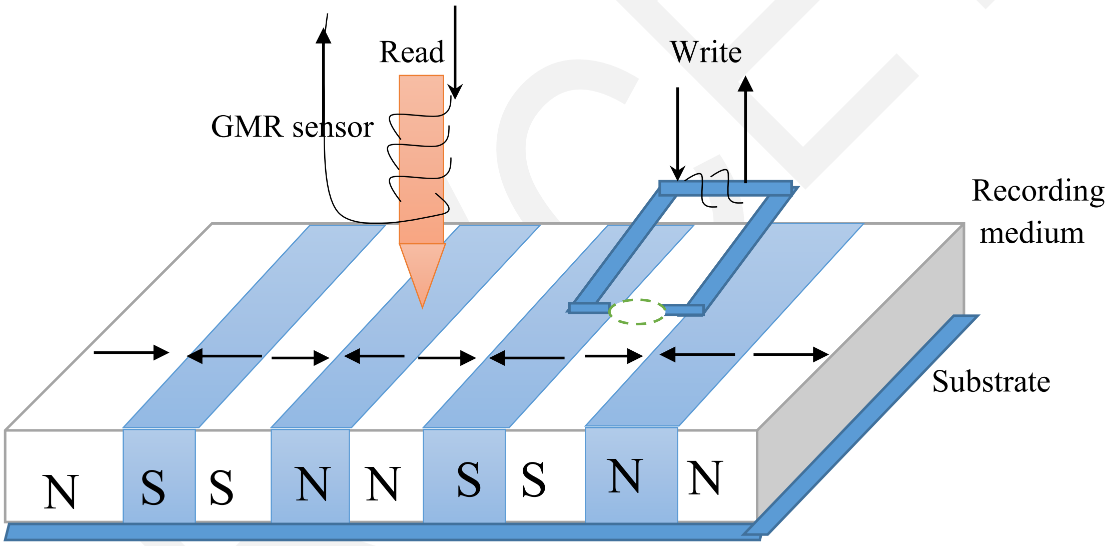
Construction

The HD consists of recording medium madeup of thin layer of magnetic garnets grown over the substrate. The GMR sensor, which is made up of ferrites and antiferromagnetic materials is used as reading element. The writing element is madeup of inductive magnetic transducer. The writing element and the GMR sensor shall be made to slide over the recording media in the longitudinal direction as shown in figure. Hence this method is also called as longitudinal recording. The flow of current through the GMR sensor and writing element shall be adjusted and in turn the magnetization is sensed (or) controlled in the recording media.

Working

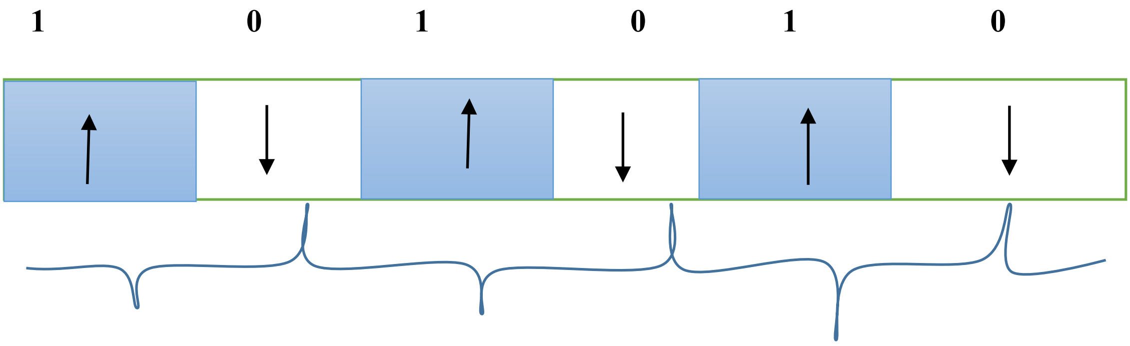
Writing / Storing

1. Initially the current is passed through the writing element and a magnetic field is induced in between the gap of the inductive magnetic transducer.
2. During writing, the amplitude of current is kept constant, and the direction of current is reversed.
3. Due to reversal of current, the magnetization orientation is reversed in the recording medium i.e., from south → North as shown in figure
4. When the induced magnetic field is greater than the coercivity of the recording media, then data is recorded in the form of 1.
5. Thus one (1) is stored as data in the recording medium as a magnetic transition.
6. When there is no magnetic transition, then it is referred as zero (0).
7. In this way the zero's (0's) and one's (1's) are stored in the recording medium.



Reading / Retrieving

1. Giant Magnetoresistive (GMR) effect is the principle used to read / retrieve the data from the recording medium.
2. When the GMR sensor is made to move near the recorded medium, then the resistance of the GMR sensor varies with respect to the orientation of the magnetic moments as follows.
3. When the layers are magnetized in parallel manner, then the resistance in the GMR sensor is minimum and therefore maximum current flows through the sensor, which represents the data as one (1)
4. When the layers are magnetized in antiparallel manner, then the resistance in the GMR sensor is maximum and therefore minimum(or) almost no current flows through the sensor, which represents the data as zero (0)
5. Therefore with the help of the reading current, the zero's (0's) and one's (1's) can be retrieved from the magnetic hard disk drive.



Advantages

- HDD can store the data in terabytes
- It has very large storage capacity
- It is compact in size and can be easily transferred from one place to another.
- The size of recording medium is reduce up to few nano meter range using nanotechnology
- GMR sensor are non-diffusive and are very sensitive in reading

Disadvantages

- HDD is slower than soli state drives
- Consume large power
- Data may be corrupted due to thermal radiation
- HDD has bulkier form factor
- GMR noise ratio is high for nano size recording media

Applications

- Used as storage devices in cloud applications
- Used in coding and signal processing units
- Used in control systems, Nano electronics, etc.,