2. Magnetic Properties of Materials

2.1. Introduction

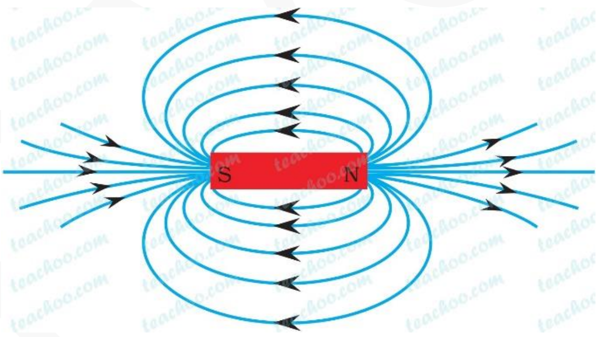
A very large number of modern devices depends upon magnetic properties of materials for their working. For example, the speakers, electrical power generators, electrical machines, transformers, television, data storage devices like magnetic tapes and disks, magnetic compass etc., Magnetic Resonance Imaging (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.

2.2. 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.

2.3. 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.

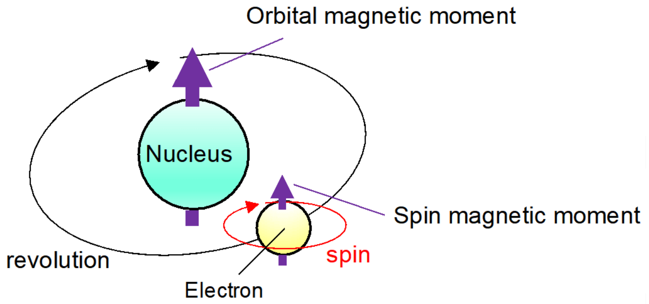
(i) Magnetic moment due to the movement of electrons in orbits around the nucleus, i.e., due to orbital angular momentum. This is called the orbital magnetic moment.

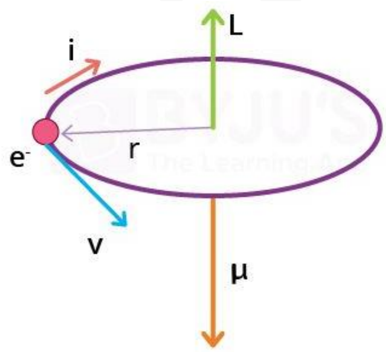
(ii) Magnetic moment due to spin of the electrons, i.e., due to spin angular momentum . This is called spin magnetic moment.

(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

__**Orbital angular momentum of the electrons:-**__ 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 $I = \dfrac{\text{Charge of electron (-e)}}{\text{Time (T)}}$ (1)

But $T = \dfrac{2\pi}{\omega}$ (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 $\omega = \dfrac{v}{r}$ (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 $\mu_B = 9.27 \times 10^{-24}$ Am^2

2.4. 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

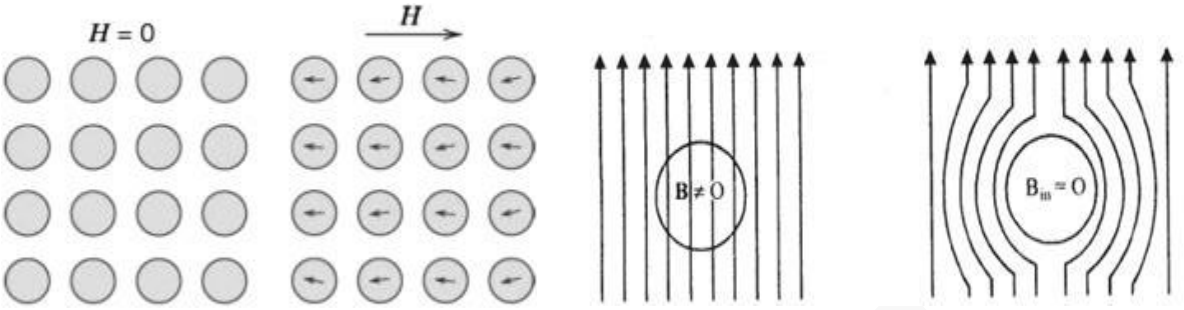
(1) **Diamagnetic materials** - no permanent magnetic moment

(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.

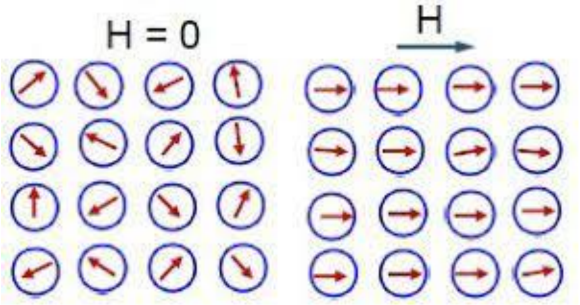
(3) The magnetic susceptibility is negative and it does not depend on temperature and applied magnetic field strength

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

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

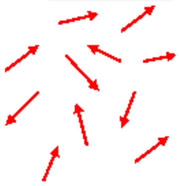
(or) $\chi = \frac{C}{T}$

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

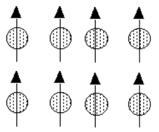
These materials show the spontaneous magnetisation. i.e., they have magnetization (atomic magnetic moments are aligned) even in the absence of an external magnetic field. This indicates that there is a strong internal field within the material which makes the atomic magnetic moment align with each other. 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 $\chi = \frac{C}{T-\theta}$ for (T > θ, paramagnetic; T < θ, ferromagnetic). Here C is Curie's constant.

2.5. Domain theory of ferromagnetism

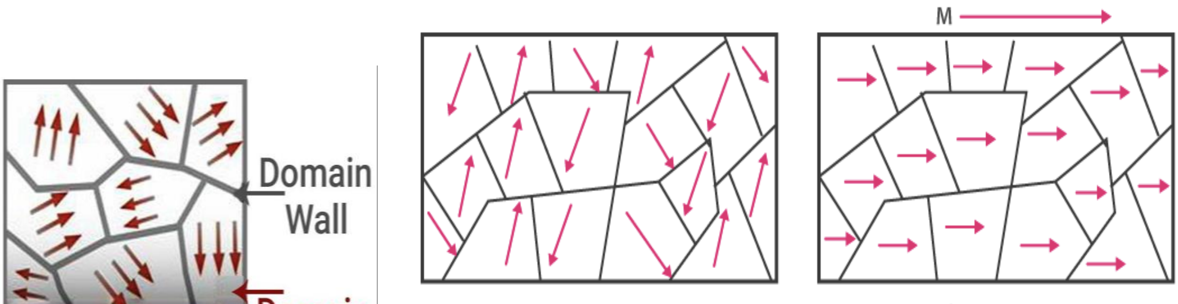
Weiss proposed the concept of domains in order to explain the properties of ferromagnetic materials.

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.

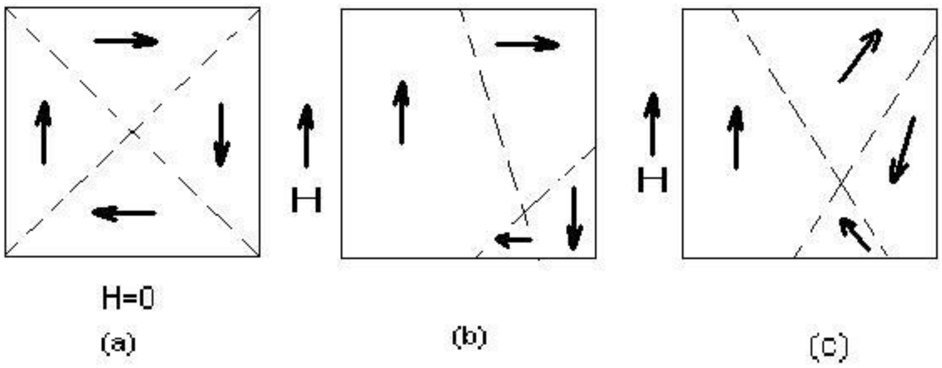
However, the domain walls are thicker than the grain boundaries. Like grain growth, *the domain size* can also grow due to the movement of domain walls. When a magnetic field is applied externally to a ferromagnetic material, the domains align themselves with field as shown in figure. This results in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

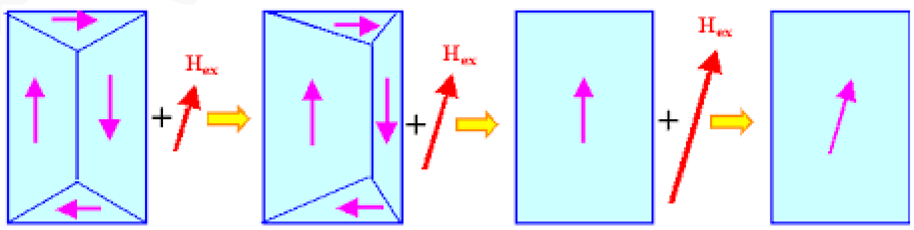
Process of domain magnetization

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.





(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.

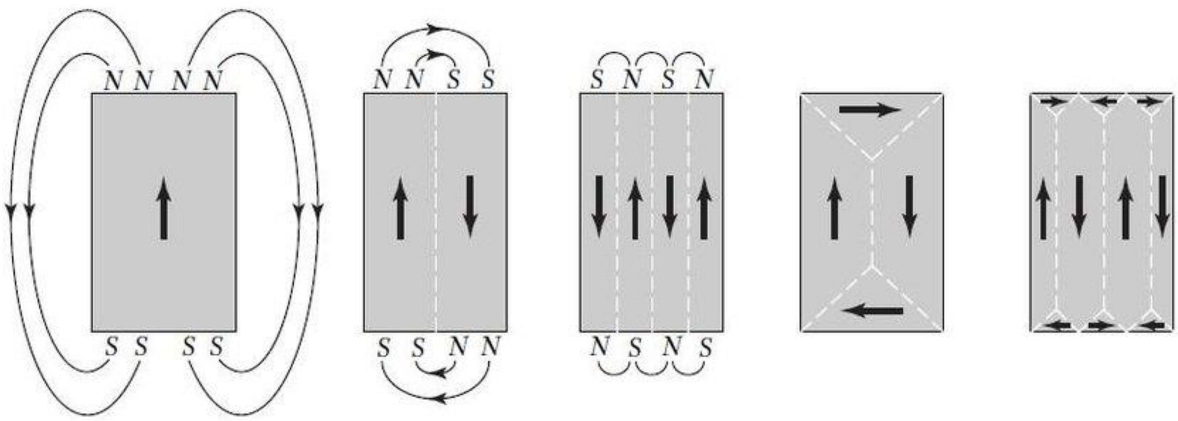
2.6. Types of energy involved in the process of domains growth

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.



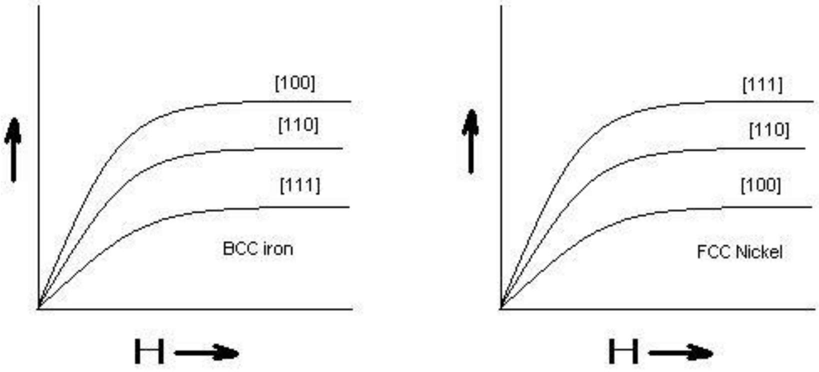
(a) (b) (c) (d) (e)

(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)



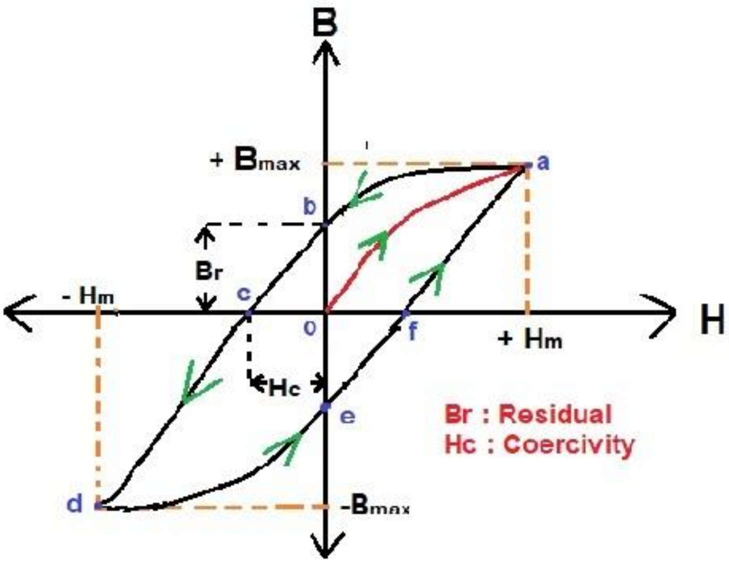
From the figure, it is clear that, BCC iron require much greater fields to produce magnetic saturation in [111] direction as compared to the field required in [100] direction. Here the difference in magnetic energy to produce magnetic saturation in an easy [100] direction and [111] direction is called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

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)

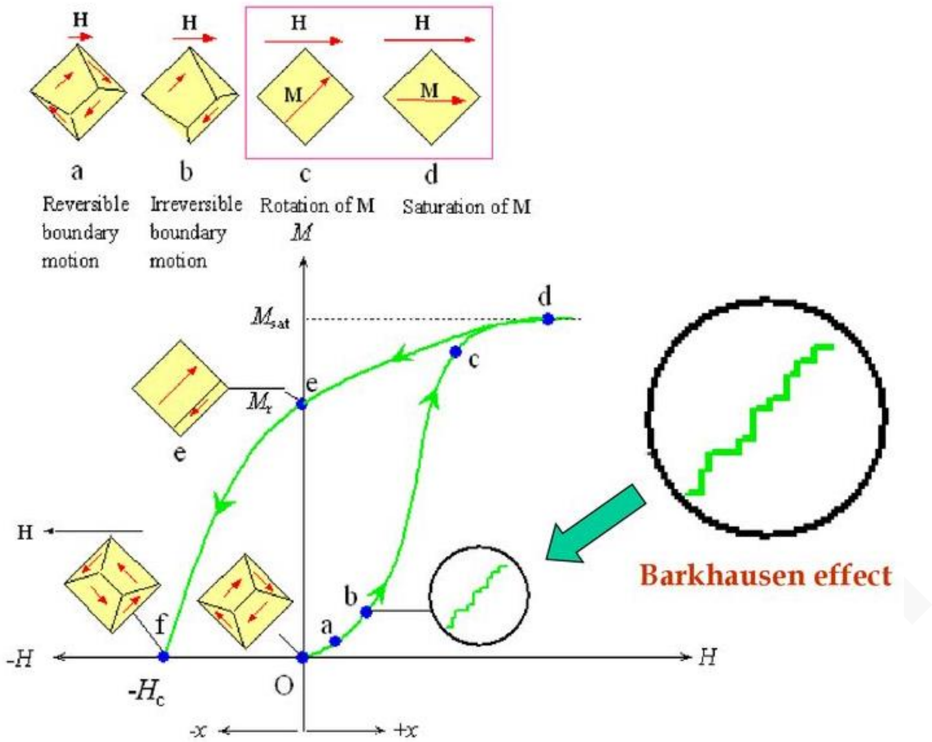
Coercivity or Coercive force

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.

2.7. 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 '$\mathbf{M_s}$'. At this position, even after the removal of external field the material possess residual magnetization called **"Retentivity"** represented by "OE" in figure

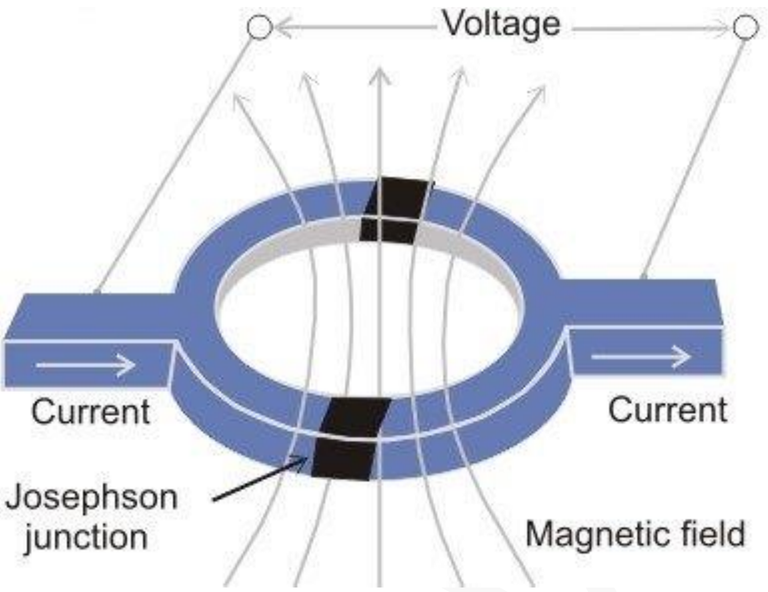
Actually after the removal of the external field, the specimen will try to attain the original configuration by the movement of Bloch wall. But this movement is stopped due to the presence of impurities, lattice imperfections, etc., therefore to overcome this, a large amount of reverse magnetic field 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.

2.8. Superconducting Quantum Interference Devices (SQUID)

SQUIDS are the improved model of Josephson devices. It has high efficiency, sensitivity and quick performance.



Principle

Small change in magnetic field, produces variation in the flux quantum

Explanation

It consists of a superconducting ring which can have magnetic fields of quantum values (1, 2. 3,..) of flux placed in between the two Josephson junctions as shown in figure. When the magnetic field is applied perpendicular to the plane of the ring, current is induced at the two Josephson junctions and produces interference pattern. The induced current flows around the ring can have quantum value of flux, which corresponds to the value of magnetic field applied. Therefore SQUIDs are used to detect the variation in very minute magnetic signals in term of quantum flux. They are used as storage devices for magnetic flux. They are also used in the study of earth quakes, removing paramagnetic impurities, detection of magnetic signals from the brain, herat, etc.,

2.9. 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.

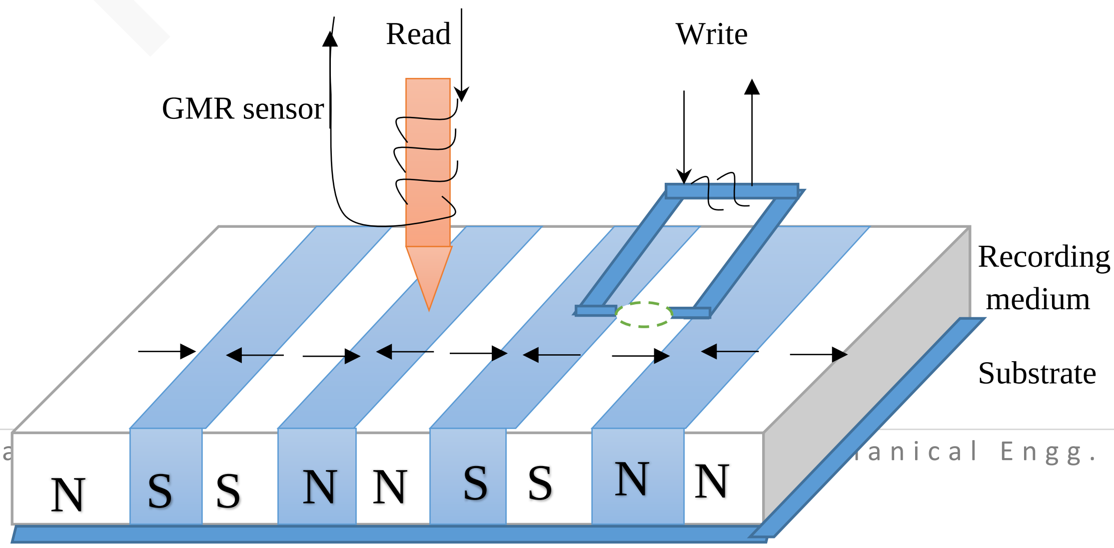
Construction

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

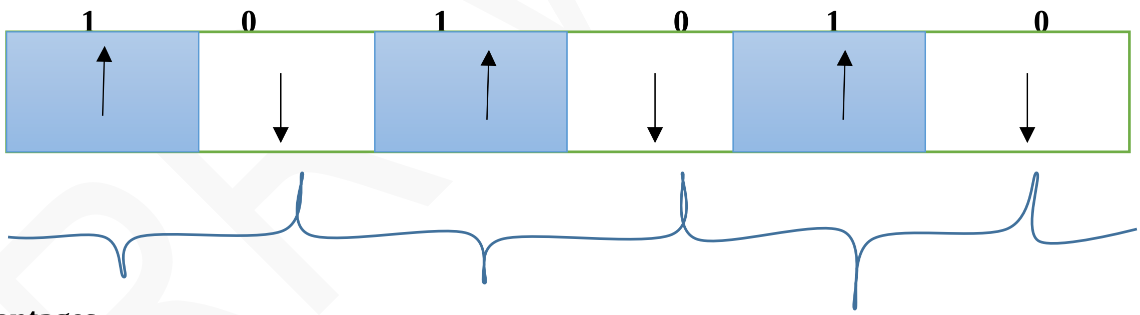
Writing / Storing

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

12. **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.

13. **What is Curie temperature?**
It is the critical temperature below which a material can behaves as ferromagnetic material and above which it can behave as paramagnetic material.
14. **Define spontaneous magnetization and discuss the same at low and high temperature.**
The molecular magnets in ferromagnetic materials are aligned in such a way that they exhibit a magnetization even in the absence of an external magnetic field This phenomenon is known as spontaneous magnetization.
At low temperatures the spontaneous magnetization is high and at high temperatures the spontaneous magnetization becomes zero.
15. **What is meant by magneto-static energy and magnetostrictive energy?**
Magnetostatic energy
The interaction energy which makes the adjacent dipoles to align themselves is known as magnetostatic energy. Since this energy is in the form of potential energy it is called magneto-static energy.
16. **What is GMR?**
If the charge in electrical resistance is very high compared to the magnetisation, it is called as Gaint Magneto-Resistance (GMR) and this effect is called GMR effect.

Part – B Question and Answers

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

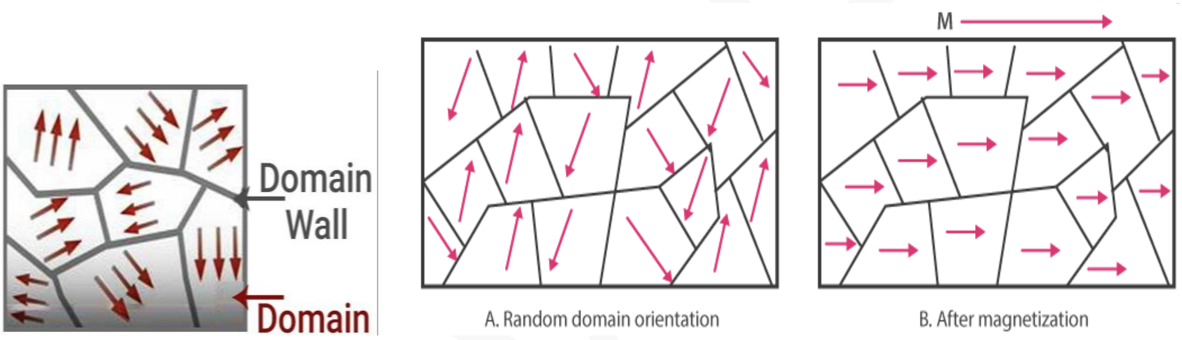
Weiss proposed the concept of domains in order to explain the properties of ferromagnetic materials.

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.

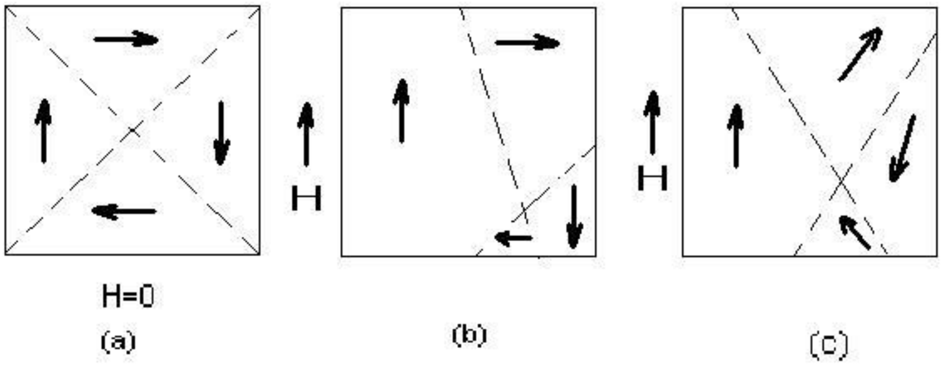
However, the domain walls are thicker than the grain boundaries. Like grain growth, *the domain size* can also grow due to the movement of domain walls. When a magnetic field is applied externally to a ferromagnetic material, the domains align themselves with field as shown in figure. This results in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

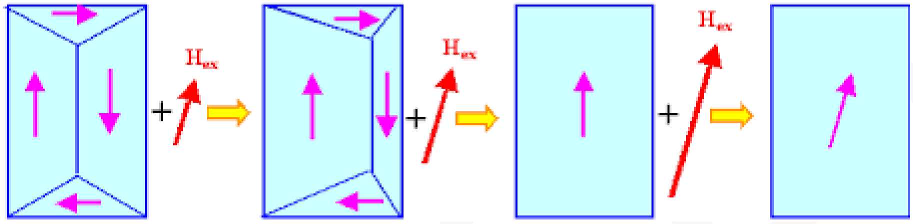
Process of domain magnetization

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

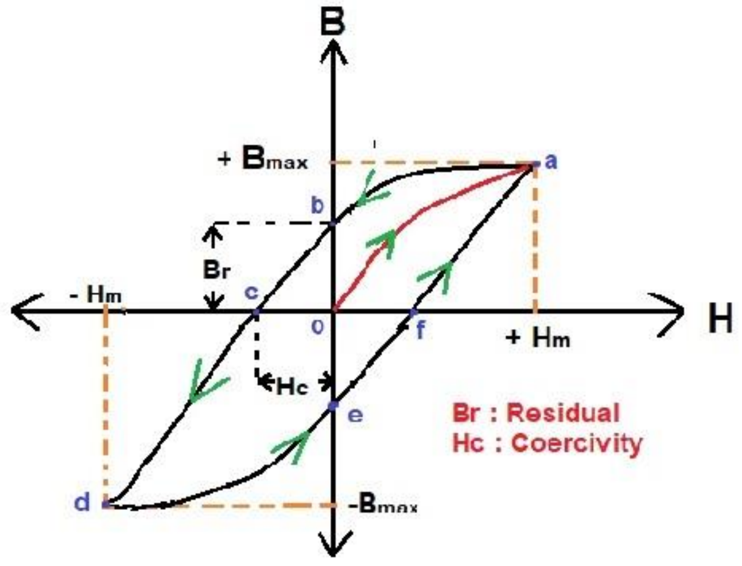
As the magnetic field is increased to a large value (i.e., near saturation) further domain growth becomes impossible through domain wall movement. Therefore, most favourably oriented and fully grown domains tends to rotate so as to be in complete alignment with the field direction as shown in figure.

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)

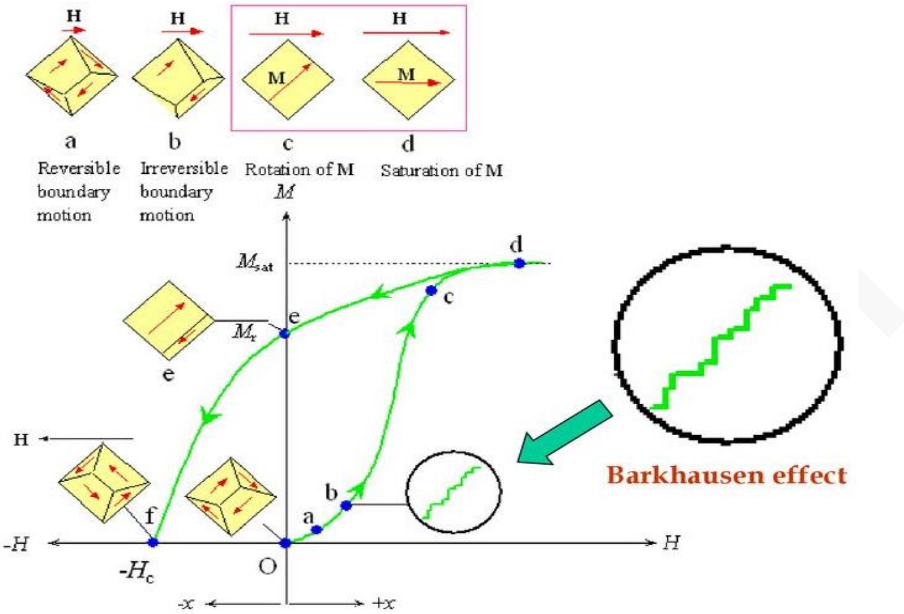
Coercivity or Coercive force

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.

2. 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 '$\mathbf{M_s}$'. 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. What are the different types of energies involved in domain theory of ferromagnetism?

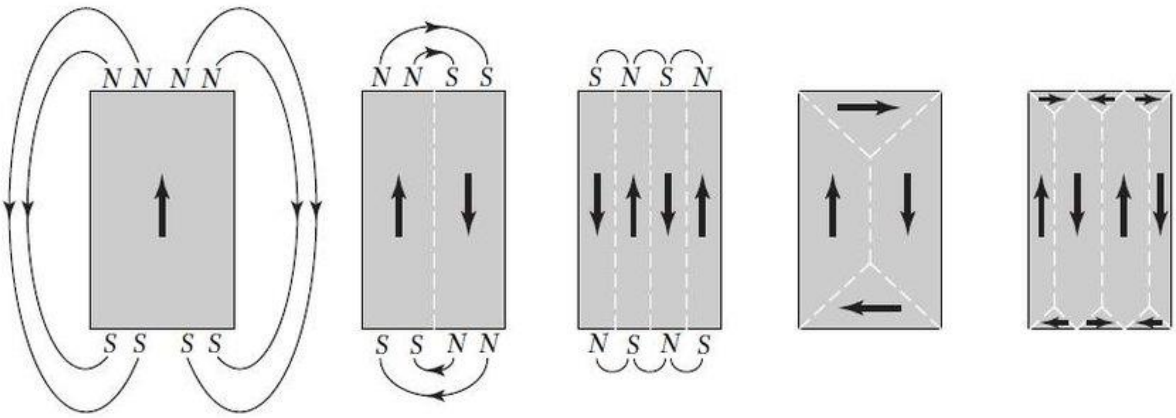
To study the domain structure clearly, we must know four types of energy involved in the process of domain growth. They are:

(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.



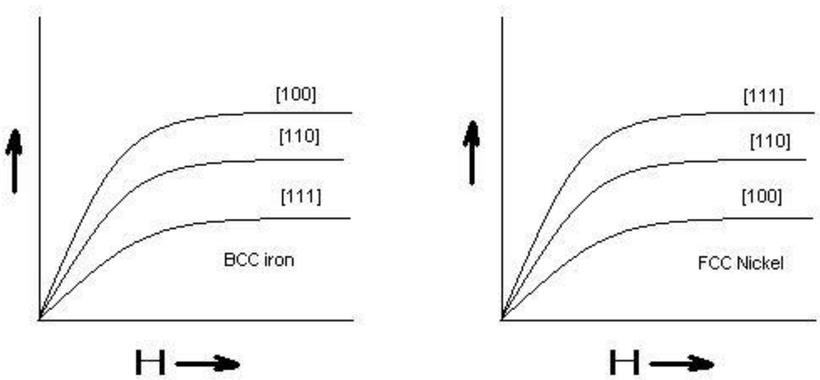
(a) **(b)** **(c)** **(d)** **(e)**

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)



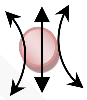
From the figure, it is clear that, BCC iron require much greater fields to produce magnetic saturation in [111] direction as compared to the field required in [100] direction. Here the difference in magnetic energy to produce magnetic saturation in an easy [100] direction and [111] direction is called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

4. 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.

5. 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.

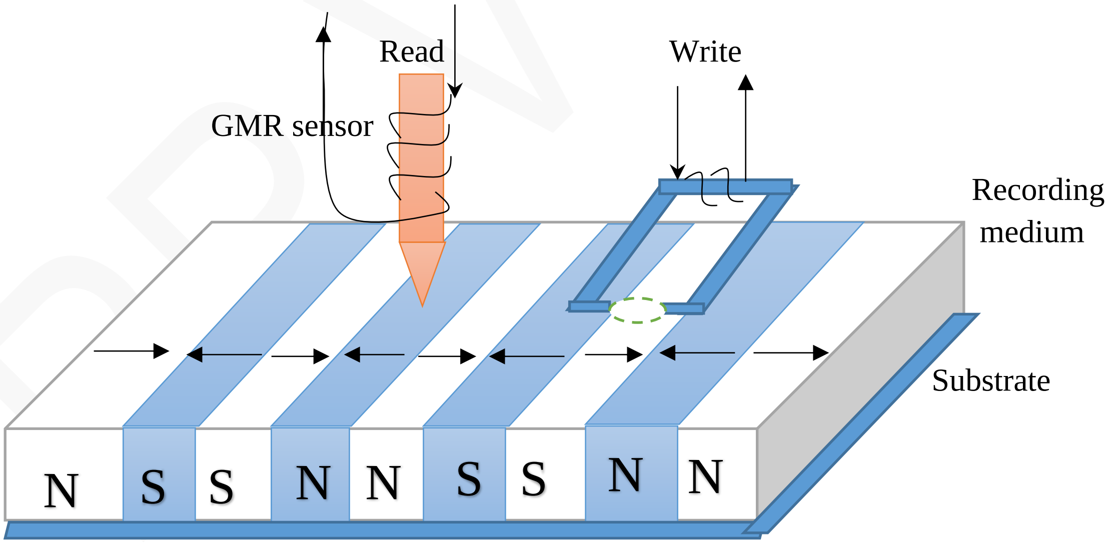
Construction

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

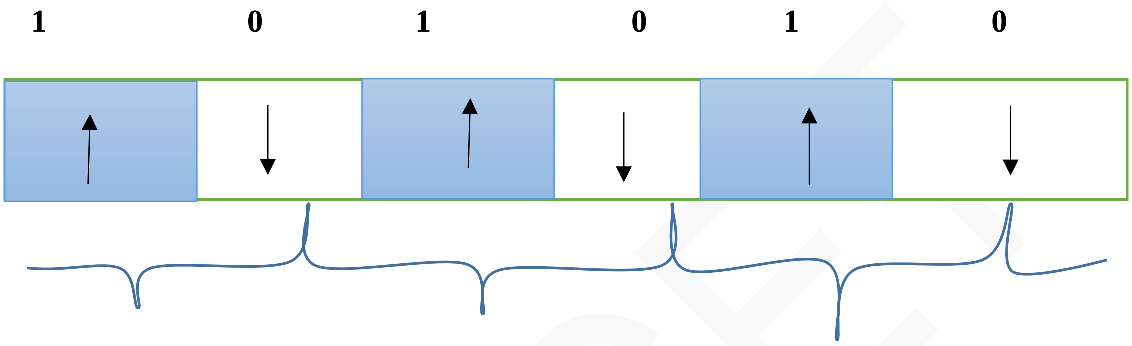
1. Initially the current is passed through the writing element and a magnetic field is induced in between the gap of the inductive magnetic transducer.
2. During writing, the amplitude of current is kept constant, and the direction of current is reversed.
3. Due to reversal of current, the magnetization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

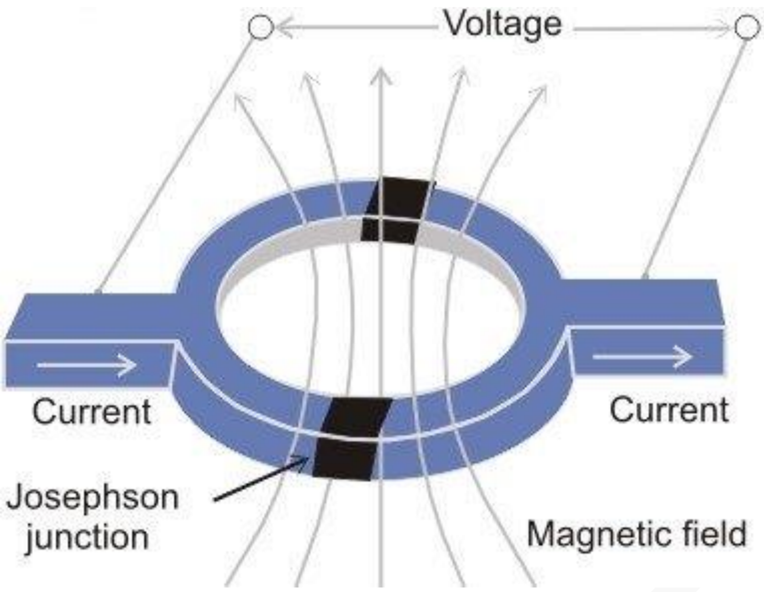
- HDD is slower than soli state drives
- Consume large power
- Data may be corrupted due to thermal radiation
- HDD has bulkier form factor
- GMR noise ratio is high for nano size recording media

Applications

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

6. Describe the working of Superconducting Quantum Interference Device (SQUID).

SQUIDS are the improved model of Josephson devices. It has high efficiency, sensitivity and quick performance.



Principle

Small change in magnetic field, produces variation in the flux quantum

Explanation

It consists of a superconducting ring which can have magnetic fields of quantum values (1, 2. 3,..) of flux placed in between the two Josephson junctions as shown in figure. When the magnetic field is applied perpendicular to the plane of the ring, current is induced at the two Josephson junctions and produces interference pattern. The induced current flows around the ring can have quantum value of flux, which corresponds to the value of magnetic field applied. Therefore SQUIDs are used to detect the variation in very minute magnetic signals in term of quantum flux. They are used as storage devices for magnetic flux. They are also used in the study of earth quakes, removing paramagnetic impurities, detection of magnetic signals from the brain, herat, etc.,