SVR ENGINEERING COLLEGE

PHYSICS OF ELECTRONIC MATERIALS & DEVICES

by

N. DIVYA MANJIRA

5.Magnetic Materials and their applications

Introduction:

Magnetic Materials play a prominent role in modern technology. They are widely used in industrial electronics, entertainment electronics and computer industry.

Magnetism is a fundamental force of nature that arises from the movement of charged particles, particularly electrons. It is characterized by attractive or repulsive forces between objects with magnetic properties. Magnets are objects that generate magnetic fields, which can exert forces on other magnets or magnetic materials.

Key concepts related to magnetism include:

1.*Magnetic Field*, **H**: A magnetic field is a region of space where a magnetic force can be detected. It is represented by lines of force called magnetic field lines. The magnetic field is generated by moving charges, such as electrons. It is denoted by H. The units of **H** are ampere-turns per metre (A/m) in SI system.

2.*Magnetic Poles*: Magnets have two poles, commonly referred to as the north pole (N) and the south pole (S). Unlike poles attract each other, while like poles repel each other. This behaviour is described by the magnetic poles' property of polarity.

3.*Magnetic Induction,* B*:* A magnetic field is schematically represented by lines of magnetic induction (or magnetic flux density).

The lines of induction are collectively called ***flux***. The number of field lines passing through a unit area of cross-section is called the ***magnetic flux density***, **B**.

$$B = \frac{\text{Magnetic flux}}{\text{area}} = \frac{\varphi}{\mathbf{A}}$$

The quantity B is measured in weber per square metre (Wb/m^2) or tesla (T). The cgs unit for magnetic induction is the gauss (G).

$$1\ G = 10^{-4}\ T$$

4. ***Magnetization,* M** : Magnetization is defined as the magnetic moment per unit volume developed inside a solid and is denoted by M. In SI system, magnetization is measured in amperes per metre (A/m).

5.*Magnetic Susceptibility, χ :* The magnetic susceptibility of a material is a measure of how much the material can be magnetized.

$$\chi = \frac{\mathbf{M}}{\mathbf{H}}$$

Magnetic Materials :

Magnetic materials are substances that exhibit magnetic properties, meaning they can be attracted to or repelled by a magnet. These materials possess microscopic regions called magnetic domains, where the magnetic moments of individual atoms or ions are aligned in a similar direction. When these domains align on a larger scale, the material as a whole displays a macroscopic magnetic field.

There are generally five types of magnetic materials:

1.***Ferromagnetic materials***: These are the most common type of magnetic materials and exhibit strong magnetic properties. They can be magnetized and retain their magnetism even after the external magnetic field is removed. Examples include iron, nickel, cobalt, and their alloys. Ferromagnetic materials are widely used in the production of magnets.

2.*Paramagnetic materials*: Paramagnetic materials have weak magnetic properties and are only attracted to an external magnetic field. When exposed to a magnetic field, the atoms or molecules in paramagnetic materials align their magnetic moments in the direction of the field, but the alignment is temporary and disappears once the external field is removed. Examples include aluminum, platinum, and oxygen.

3.***Diamagnetic materials***: Diamagnetic materials exhibit a weak repulsion when placed in an external magnetic field. Unlike paramagnetic materials, diamagnetic materials have all their atomic or molecular magnetic moments aligned opposite to the direction of the applied field. Examples include copper, zinc, silver, and water. Diamagnetic materials are not commonly used for their magnetic properties.

4.*Ferrimagnetic materials*: Ferrimagnetic materials possess both ferromagnetic and paramagnetic properties. They exhibit spontaneous magnetization, but the magnetic moments of the atoms or ions in the material are not completely aligned, resulting in a net magnetic moment. Ferrimagnetic materials can be found in certain types of magnetic minerals, such as magnetite (Fe3O4).

5.*Antiferromagnetic materials*: Antiferromagnetic materials have magnetic moments on individual atoms or ions, but these moments are aligned in opposite directions, resulting in a net magnetization of zero. The magnetic interactions between neighbouring moments cause them to align anti-parallel to each other. Antiferromagnetic materials exhibit no overall magnetic behaviour at macroscopic scales. Manganese oxide (MnO) is an example of an antiferromagnetic material.

These five types of magnetic materials exhibit different magnetic properties, which make them suitable for various applications in fields such as electronics, energy generation, and data storage.

Various Contributions to para magnetism :

Para magnetism is a form of magnetism exhibited by certain materials that are weakly attracted to an external magnetic field. It arises due to the presence of unpaired electrons in the atomic or molecular orbitals of the material. Several factors contribute to paramagnetism. Here are some of the key contributions:

1.Unpaired electrons: Paramagnetic materials possess atoms, ions, or molecules with unpaired electrons. These unpaired electrons have magnetic moments associated with them, which align with an external magnetic field, resulting in an attractive force.

2.Magnetic moments of atoms: Each atom in a paramagnetic material possesses an intrinsic magnetic moment due to the spin and orbital motion of its electrons. When an external magnetic field is applied, these atomic magnetic moments tend to align with the field, resulting in a net magnetic moment and attraction.

3.Electron spin: The spin of electrons plays a crucial role in paramagnetism. Electrons have an intrinsic property called spin, which gives rise to their magnetic moment. Unpaired electrons in paramagnetic materials contribute significantly to the total magnetic moment of the material.

4.Electron motion and orbital angular momentum: In addition to spin, the orbital motion of electrons around the atomic nucleus also generates a magnetic moment. The orbital angular momentum of electrons adds to the overall magnetic moment of the material and contributes to paramagnetism.

5.Thermal energy: At higher temperatures, thermal energy disrupts the alignment of atomic or molecular magnetic moments, reducing the overall magnetization and weakening the paramagnetic response. However, even at room temperature, certain paramagnetic materials can exhibit noticeable magnetism.

6.Magnetic susceptibility: The extent of paramagnetism is quantified by the magnetic susceptibility, which represents the material's response to an applied magnetic field. The susceptibility is influenced by the factors mentioned above and can be measured experimentally.

7. Curie's law : This law indicates that the susceptibility χ of paramagnetic materials is inversely proportional to their temperature. Curie's law is only valid under conditions of low magnetisation.

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

where the susceptibility is inversely proportional to the absolute temperature, T and C is the curie constant.

It is important to note that paramagnetism is a temporary magnetism that diminishes when the external magnetic field is removed. It is distinct from ferromagnetism or anti ferromagnetism, which exhibit long-range ordering and retain magnetization in the absence of an external field.

Various Contributions to dia magnetism :

Diamagnetism is a property exhibited by certain materials that are weakly repelled by an external magnetic field. Unlike paramagnetic materials, diamagnetic materials do not possess unpaired electrons. Instead, their diamagnetic response arises from the orbital motion of electrons and the magnetic field-induced currents that oppose the applied field.

Here are the key contributions to diamagnetism:

1.Electron orbital motion: Diamagnetic materials have paired electrons occupying their atomic or molecular orbitals. When subjected to an external magnetic field, the orbital motion of these paired electrons generates small circulating currents. These induced currents create a magnetic field that opposes the applied field, resulting in a net repulsive force.

2.Lenz's law: Diamagnetism follows Lenz's law, which states that the direction of the induced current opposes the change that caused it. When an external magnetic field is applied, it induces a current in the diamagnetic material that generates a magnetic field opposing the applied field. This opposing field leads to repulsion.

3.Magnetic susceptibility: Diamagnetic materials have a negative magnetic susceptibility, indicating their weak repulsive response to an applied magnetic field. The susceptibility arises due to the cancellation of magnetic moments within the material caused by the pairing of electrons in the orbitals.

4.Meissner effect (superconductors): In the case of superconductors, which exhibit perfect diamagnetism, an additional phenomenon known as the Meissner effect occurs. When a superconductor is cooled below its critical temperature, it expels almost all magnetic fields from its interior, resulting in complete diamagnetic behaviour. This effect is a consequence of the perfect conductivity and formation of superconducting electron pairs known as Cooper pairs.

It's important to note that diamagnetism is a relatively weak effect compared to paramagnetism or ferromagnetism. In most materials, the diamagnetic contribution is overshadowed by other magnetic properties. However, it plays a significant role in the behaviour of superconductors and is observable in certain materials when other magnetic contributions are absent or negligible.

Various Contributions to Ferromagnetism :

Ferromagnetism is a phenomenon in which certain materials exhibit a strong permanent magnetization even in the absence of an external magnetic field. These materials are called ferromagnetic materials and include substances such as iron, nickel, cobalt, and some of their alloys. Ferromagnetism arises from the interaction between atomic magnetic moments within the material.

Here are the key contributions to ferromagnetism:

1.Electron spin: Ferromagnetic materials have unpaired electrons with aligned spins, resulting in a net magnetic moment for each atom. These atomic magnetic moments align parallel to each other within small regions called domains.

2.Exchange interaction: The alignment of atomic magnetic moments is due to the exchange interaction between neighbouring atoms. This interaction, which is a quantum mechanical effect, favours parallel alignment of spins, leading to the formation of magnetic domains with aligned moments.

3.Domain structure: Ferromagnetic materials are composed of numerous magnetic domains, where the magnetic moments within each domain are aligned. The size and arrangement of domains depend on factors such as temperature and external magnetic field. In an unmagnetized state, the domains are randomly oriented, resulting in a net magnetization of zero.

4.Spontaneous magnetization: When an external magnetic field is applied, it aligns the domains in the same direction, resulting in a net magnetization of the material. The alignment of domains is retained even after removing the external field, creating a permanent magnet.

5.Curie temperature: Ferromagnetic materials have a critical temperature called the Curie temperature (Tc). Above this temperature, thermal energy disrupts the alignment of magnetic moments, causing a loss of magnetization. Below the Curie temperature, ferromagnetic materials exhibit spontaneous magnetization and retain their magnetic properties.

6.Hysteresis: Ferromagnetic materials exhibit hysteresis, which means that the magnetization lags behind the applied magnetic field during magnetization and demagnetization processes. The hysteresis loop represents the relationship between the magnetic field and the magnetization, and it depends on the material's magnetic properties.

Ferromagnetism is a key property in the field of magnetism and finds applications in various technologies, including magnetic storage devices, transformers, motors, and magnetic sensors. Understanding and controlling ferromagnetic behaviour is crucial for the development of magnetic materials with desired properties.

Various Contributions to Ferrimagnetism :

Ferrimagnetism is a type of magnetism characterized by the presence of magnetic moments that align in an antiparallel manner but do not cancel each other out completely, resulting in a net magnetization. This phenomenon arises from the interactions between different types of magnetic ions or atoms within a material. Several factors contribute to the development of ferrimagnetism.

Here are some of the key contributions :

1.Magnetic Ions: Ferrimagnetism typically occurs in materials that contain different types of magnetic ions, such as transition metals. These ions have partially filled d or f orbitals, which give rise to unpaired electrons and their associated magnetic moments.

2.Exchange Interactions: The magnetic ions in a ferrimagnetic material interact with each other through exchange interactions. These interactions can be classified into two types: ferromagnetic and antiferromagnetic. Ferromagnetic interactions favour parallel alignment of magnetic moments, while antiferromagnetic interactions favour antiparallel alignment.

3.Magnetic Sublattices: In ferrimagnetic materials, the different types of magnetic ions occupy separate sublattices or crystallographic sites within the material's structure. The magnetic moments within each sublattice tend to align parallel to each other, while the sublattices themselves may have opposite alignments.

4.Magnetic Domains: Ferrimagnetic materials often exhibit the formation of magnetic domains. Within each domain, the magnetic moments are aligned in a specific direction, resulting in a net magnetization. However, different domains may have different orientations, leading to a partial cancellation of magnetization at the macroscopic level.

5.Magnetic Anisotropy: Magnetic anisotropy refers to the dependence of a material's magnetic properties on the direction of an external magnetic field. Anisotropy can influence the alignment of magnetic moments and contribute to the stability of the ferrimagnetic ordering.

6.Crystal Structure: The crystal structure of a ferrimagnetic material can also affect its magnetic properties. The arrangement of atoms or ions in the lattice determines the distances and angles between neighbouring magnetic moments, influencing the strength of exchange interactions and the overall magnetic behavior.

These various contributions collectively give rise to the distinctive properties of ferrimagnetic materials, such as a net magnetization and hysteresis behavior. Ferrimagnets are commonly found in magnetic oxides, such as magnetite (Fe_3O_4), where the presence of both Fe^{2+} and Fe^{3+} ions leads to a ferrimagnetic arrangement.

Various Contributions to Ferrites :

Ferrites are a class of ceramic materials that exhibit ferrimagnetic properties. They are composed of iron oxide (Fe_2O_3) combined with one or more other metal oxides, such as zinc, manganese, nickel, or cobalt. The specific contributions to the magnetic properties of ferrites can vary depending on the composition and structure of the material.

Here are some of the key contributions:

1.Magnetic Ions: The presence of magnetic ions, particularly iron ions (Fe^{3+}), is essential for the development of ferrimagnetic behavior in ferrites. These ions have unpaired electrons in their d orbitals, leading to the presence of magnetic moments.

2.Crystal Structure: The crystal structure of ferrites plays a crucial role in their magnetic behavior. Ferrites commonly adopt a spinel crystal structure, where metal ions occupy both tetrahedral and octahedral sites within a cubic close-packed oxygen lattice. This arrangement allows for interactions between different metal ions and the formation of magnetic sublattices.

3.Exchange Interactions: Exchange interactions between magnetic ions in ferrites are responsible for aligning the magnetic moments and contributing to ferrimagnetic ordering. The strength and nature of these interactions depend on factors such as the distance between ions, their oxidation states, and the type of metal ions present.

4.Magnetic Sublattices: In ferrites, different metal ions occupy distinct crystallographic sites or sublattices. The magnetic moments associated with these ions tend to align parallel to each other within their respective sublattice. However, the sublattices may have opposite alignments, leading to a net magnetization.

5.Magnetic Anisotropy: Magnetic anisotropy influences the preferred orientation of the magnetic moments within ferrites and determines their response to an external magnetic field. It arises due to structural or compositional factors and can affect the magnetic properties, including coercivity and remanence.

6.Domain Structure: Ferrites typically exhibit the formation of magnetic domains, where groups of atoms have aligned magnetic moments. The arrangement and size of these domains can influence the macroscopic magnetic behavior of the material.

7.Doping and Substitution: The introduction of dopant ions or substitution of metal ions in ferrites can alter their magnetic properties. Doping can modify the exchange interactions, anisotropy, and magnetic moments, allowing for the tailoring of ferrite properties for specific applications.

The contributions mentioned above collectively determine the magnetic behavior of ferrites, including their saturation magnetization, magnetic coercivity, and frequency-dependent properties. Ferrites find extensive use in applications such as permanent magnets, magnetic recording media, microwave devices, transformers, and inductors, owing to their unique magnetic characteristics.

Differences between dia, para and ferromagnetic materials :

Diamagnetics	Paramagnetics	Ferromagnetics
1.Solid,liquid,gases.	1.Solid,liquis or gas.	1.Solids and possess crystalline structure.
2.Less no.of field lines pass through the material than outside.	2.More no.of field lines pass through the material than outside.	2.Field lines are concentrated in the material.
3.Susceptibility, χ is small but negative.	3.Susceptyibility, χ is <1 but positive.	3. Susceptibility, χ is large and positive.
4.Relative permeability, μ_r is less than unity.	4.Relative permeability, μ_r is slightly greater than unity.	4.Relative permeability, μ_r is greater than unity.
5. χ is independent of temperature.	5. Obeys Curie law, i.e, $\chi = \frac{1}{T}$	5. χ decreases with temperature in a complex manner.
6. No Curie point.	6. No Curie point.	6. Have definite Curie point above which they become paramagnetic.
7. B & M vary with H linearly but no saturation is reached.	7. B &M vary with H linearly at low temp. and at high field tends towards saturation.	7.B & M vary with H but not linearly and ultimately attain saturation.
8. Hysteresis is not exhibited.	8. Hysteresis is not exhibited	8. Exhibit phenomenon of hysteresis.
9.No retentivity.	9.No retentivity.	9.Possess retentivity.
10. Ex: Bismuth, mercury, silver, copper, water, air	10.Ex: Platinum, Chromium, Al, salts of Fe & Ni, Oxygen.	10. Ex: Iron, steel, cobalt, nickel.

Concepts of spin waves :

Spin waves, also known as magnons, are collective excitations of the spin degrees of freedom in a magnetic material. They can be thought of as the quanta of spin oscillations or spin waves propagating through a magnetic medium.

Here are some key concepts related to spin waves:

1.Spin: Spin is an intrinsic property of particles, such as electrons, which gives rise to their magnetic moment. It can be visualized as the intrinsic angular momentum of a particle.

2.Ferromagnetism: Ferromagnetic materials have a spontaneous magnetization, meaning their atomic spins align in the same direction, resulting in a macroscopic magnetic moment.

3.Exchange Interaction: The exchange interaction is responsible for the alignment of neighbouring atomic spins in a magnetic material. It arises from the quantum mechanical exchange of electrons and can be described by an exchange energy.

4.Heisenberg Model: The Heisenberg model is a simplified model used to describe the interaction between neighbouring atomic spins in a magnetic material. It assumes that the exchange interaction dominates and neglects other effects.

5.Dispersion Relation: The dispersion relation describes the relationship between the energy and momentum of magnons. It characterizes how the energy of a magnon depends on its wavelength or propagation vector.

6.Spin Wave Vector: The spin wave vector represents the spatial variation of the spin wave. It determines the wavelength and direction of propagation of the spin wave.

7.Spin Wave Spectrum: The spin wave spectrum refers to the range of allowed energies and momenta for spin waves in a magnetic material. It can be obtained from the dispersion relation.

8.Damping: Spin waves can undergo damping due to various mechanisms, such as interactions with impurities, phonons, or electron-electron scattering. Damping leads to the decay of spin waves over time and distance.

9.Spin Wave Excitation and Detection: Spin waves can be excited and detected experimentally using techniques like inelastic neutron scattering, spin-polarized electron microscopy, or magneto-optical Kerr effect.

Understanding spin waves is essential for studying magnetic materials and developing spintronic devices, which utilize the spin degree of freedom for information processing and storage. Spin waves have potential applications in areas such as magnetic sensors, spin wave logic devices, and magnetic crystals.

Anti-ferromagnetism :

Antiferromagnetism is a phenomenon in which neighboring atomic spins in a material align in an antiparallel manner, resulting in a net magnetization of zero. In contrast to ferromagnetic materials, where spins align parallel to each other, antiferromagnetic materials exhibit a spontaneous cancellation of magnetic moments.

The key properties of anti-ferromagnetism are :

1.Spontaneous Ordering: Antiferromagnetic materials undergo a spontaneous ordering of magnetic moments, with neighbouring moments aligning antiparallel to each other. This ordering occurs below a specific temperature called the Néel temperature (T_N).

2.Net Magnetic Moment: Unlike ferromagnetic materials, where the magnetic moments align parallel and result in a nonzero net magnetization, antiferromagnetic materials have a net magnetic moment of zero due to the antiparallel alignment.

3.Compensation Temperature: At temperatures below the compensation temperature (T_{comp}), antiferromagnetic materials exhibit a slight deviation from perfect antiferromagnetic order. The magnetic moments of different sublattices cancel each other partially, resulting in a small nonzero net magnetization.

4.Néel Vector: In antiferromagnetic materials, the direction of the antiferromagnetic ordering is described by the Néel vector. This vector represents the direction in which the magnetic moments rotate from one sublattice to another.

5.Magnetic Domains: Antiferromagnetic materials can exhibit domain structures, similar to ferromagnetic materials. In each domain, the antiferromagnetic moments are aligned in a specific direction, but different domains may have different orientations.

6.Magnetic Susceptibility: Antiferromagnetic materials typically have a negative magnetic susceptibility, meaning they exhibit a diamagnetic response to an applied magnetic field. However, the susceptibility can become positive at temperatures close to the Néel temperature.

7.Spin Dynamics: Antiferromagnetic materials can display interesting spin dynamics, such as spin waves or magnons. These excitations involve collective motion of the antiferromagnetic moments and can be studied using techniques like neutron scattering.

Domains and Domain Walls :

In the context of magnetism, domains and domain walls are key concepts that describe the spatial arrangement and boundaries of magnetically ordered regions within a magnetic material.

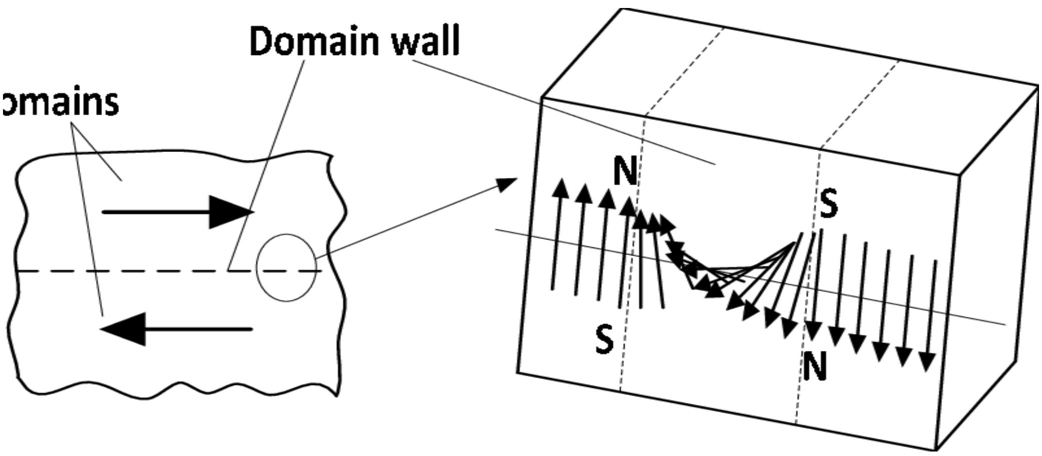
Domains: Domains are regions within a magnetic material where the atomic magnetic moments are aligned in a specific direction. In a ferromagnetic material, domains are characterized by having a net magnetization and uniform magnetization direction within each domain. However, the magnetization direction can vary between different domains. Domains form due to competing magnetic interactions and minimize the overall energy of the material.

Domain Walls: Domain walls are the interfaces or boundaries between adjacent domains with different magnetization directions. At the domain wall, the magnetic moments transition smoothly from one orientation to another. The width of a domain wall depends on various factors such as the material properties and the type of magnetic ordering. Domain walls can have different types, including Bloch walls, Néel walls, or other types depending on the magnetization rotation across the wall.

Domain Wall Dynamics: Domain walls can move and evolve under the influence of external stimuli such as magnetic fields or electrical currents. The movement of domain walls can be important for magnetic switching processes and can be utilized in various magnetic devices, such as magnetic memories and spintronic devices.

Domain Wall Pinning: Domain walls can experience pinning, where they become localized or trapped at certain defects or impurities in the material. Pinning can hinder the movement of domain walls and affect the overall magnetic behavior of the material.

Magnetic Domain Imaging: Techniques such as magnetic force microscopy (MFM) or scanning electron microscopy with polarization analysis (SEMPA) can be used to visualize and characterize magnetic domains and domain walls. These techniques provide insight into the domain structure and dynamics within a material.

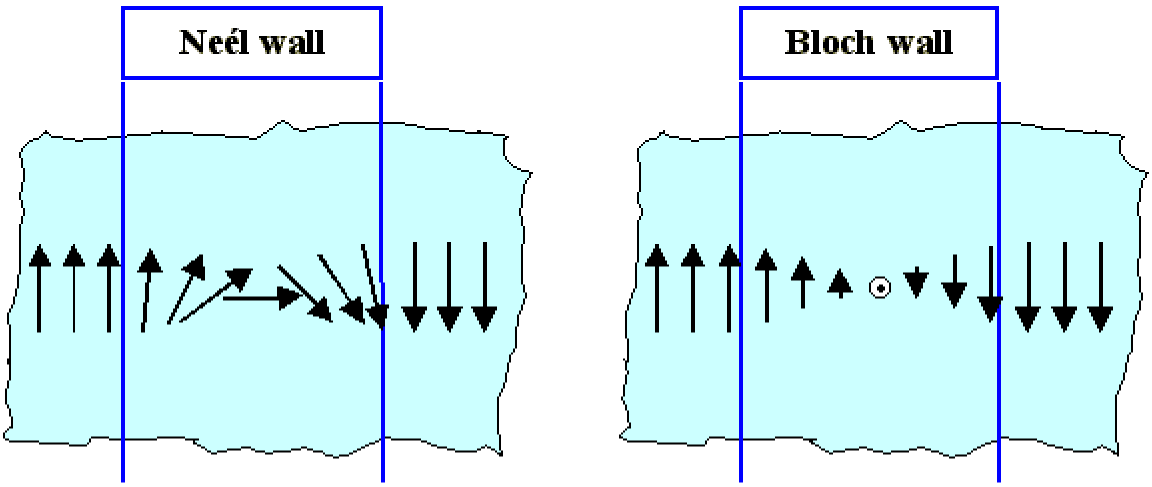


Types of domain walls :

Different types of domain walls can exist, depending on the nature of the magnetic material and the properties of the domains involved. some common types of domain walls:

1.Bloch Wall: A Bloch wall, also known as a transverse wall, is a domain wall with a gradual rotation of the magnetization direction across the wall. In a Bloch wall, the magnetization rotates in a plane perpendicular to the domain wall plane. The rotation is typically continuous, and the magnetization reaches its maximum deviation from the domain direction at the centre of the wall. Bloch walls are commonly observed in ferromagnetic materials with high magnetocrystalline anisotropy.

2.Néel Wall: A Néel wall, also called a head-to-head wall, is a domain wall where the magnetization rotates in a plane parallel to the domain wall plane. The rotation is non-continuous, and the magnetization direction changes abruptly across the wall. The magnetization at the centre of the wall points in the opposite direction to the adjacent domains. Néel walls are often found in materials with low magnetocrystalline anisotropy, such as soft magnetic materials.



3.Bloch-Like Wall: A Bloch-like wall is a domain wall that exhibits characteristics of both Bloch and Néel walls. It has a combination of gradual magnetization rotation (like a Bloch wall) and abrupt changes in the magnetization direction (like a Néel wall). The magnetization rotation occurs in a plane parallel to the domain wall plane, but the rotation is not as continuous as in a Bloch wall. Bloch-like walls are commonly observed in certain magnetic materials, such as magnetic multilayers.

4.Translational Wall: A translational wall is a domain wall that can move or translate through a material. These walls can move in response to external magnetic fields or other influences. Translational walls are important for applications such as magnetic data storage, where the ability to manipulate and control the position of domain walls is crucial.

5.Vortex Wall: A vortex wall, also known as a vortex domain wall, is a specific type of domain wall that forms in magnetic structures with a vortex-like magnetization configuration. In a vortex wall, the magnetization curls around a central point, forming a vortex-like pattern. Vortex walls have unique properties and are of interest for spintronic devices and magnetic memories.

Coercive Force or Coercivity :

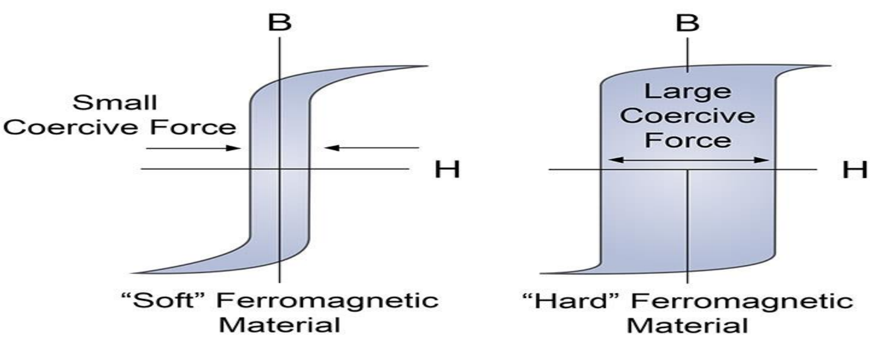
Coercive force, also known as coercivity or coercive field, is a fundamental property of magnetic materials. It measures the resistance of a material to being demagnetized or having its magnetization reversed. In simple terms, it represents the strength of an external magnetic field required to reduce the magnetization of a material to zero.

Definition: Coercive force (Hc) is the magnitude of the external magnetic field required to reduce the residual magnetization of a material to zero after it has been magnetized to saturation. It represents the ability of a material to retain its magnetization in the absence of an external field.

Measurement: Coercive force is measured in units of oersted (Oe) or amperes per meter (A/m). The measurement is typically obtained by gradually reducing the magnetic field from saturation until the magnetization of the material reaches zero.

Magnetic Hysteresis Loop: Coercive force is determined by analysing the magnetic hysteresis loop of a material. The hysteresis loop illustrates the relationship between the applied magnetic field (H) and the resulting magnetization (M) of the material. The coercive force corresponds to the magnitude of the applied field at which the magnetization becomes zero during the demagnetization process.

Soft and Hard Magnetic Materials: Materials with low coercive force are known as soft magnetic materials. They have low resistance to demagnetization and can be easily magnetized and demagnetized. Soft magnetic materials are commonly used in applications such as transformers and magnetic sensors. On the other hand, materials with high coercive force are known as hard magnetic materials. They have strong resistance to demagnetization and are used for permanent magnets in applications like motors, magnetic data storage, and magnetic couplings.



Factors Influencing Coercive Force: Coercive force depends on various factors, including the composition, microstructure, and processing of the magnetic material. It is influenced by factors such as the strength of the exchange interaction, the crystal structure, the presence of impurities, and the alignment of magnetic domains within the material.

Temperature Dependence: Coercive force can also be temperature-dependent. Some magnetic materials may exhibit a decrease in coercive force with increasing temperature, leading to decreased stability of magnetization at higher temperatures. This temperature dependence is described by the temperature coefficient of coercivity.

There are two different kinds of Coercivity- Hcb and Hcj.

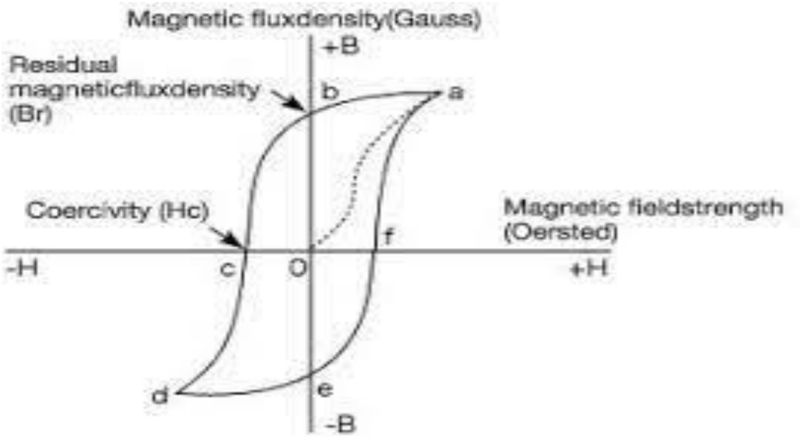
Hcb is Normal Coercivity and **Hcj** is Intrinsic Coercivity.

The Difference between Hcj and Hcb

Hcb – is called Normal Coercivity. It is the point on the BH curve where a magnet's internal field is completely canceled out by the opposing field. In other words, the net flux density is now zero because the opposing field is equal and opposite the magnet's own field. At this point, the demagnetization is still recoverable because the magnet has not lost its polarity.

If the magnet has not been taken below the "knee" the magnet's field will recover completely after the opposing field has been removed. If the magnet has been taken below the knee, it will have to be re-magnetized.

Hcj – is known as the Intrinsic Coercivity. It is the point where the magnet's polarization has been reduced to zero. At this point, the magnetic domains have lost their polarity –or anisotropy- and in the case of a sintered NdFeB magnet -or any other typical ferromagnet- they can be re-magnetized if there has been no physical damage to the magnet.

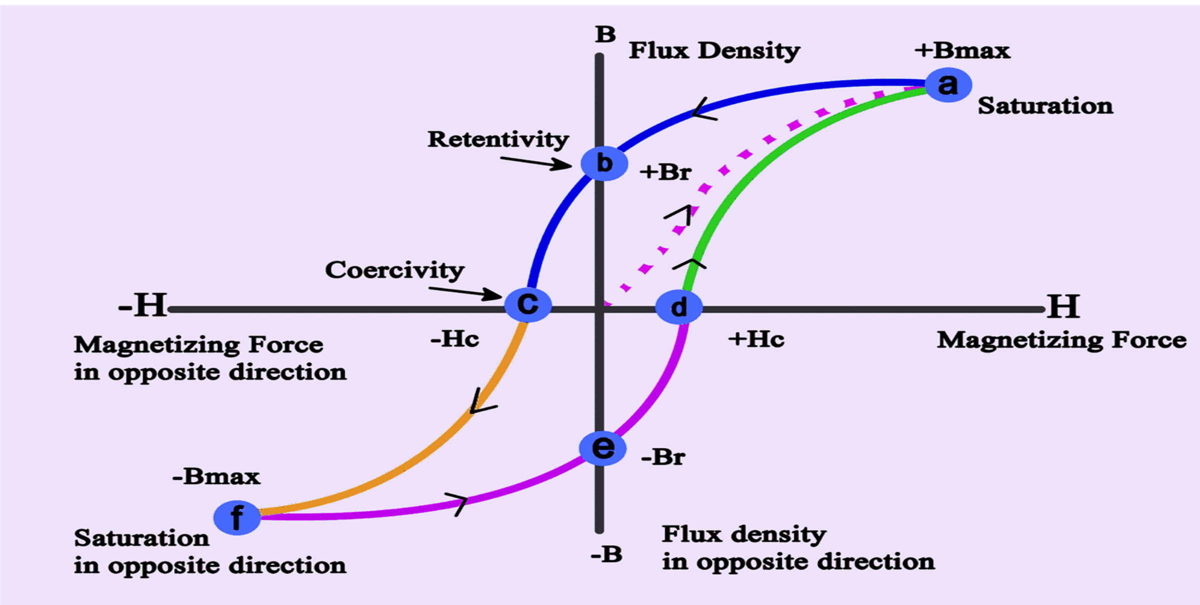


Hysteresis :

Hysteresis is an fundamental property of the behaviour of magnetic materials. Coercivity is always studied on the second quadrant of the BH curve. The BH curve is also known as the ***Hysteresis curve***.

Some key points about hysteresis in magnetism:

<u>Magnetic Hysteresis Loop</u>: The behaviour of a magnetic material under the influence of an applied magnetic field is often represented by a hysteresis loop. This loop shows the relationship between the applied magnetic field (H) and the resulting magnetization (M) of the material. The loop is obtained by sweeping the magnetic field from a negative maximum value, increasing it to a positive maximum, and then decreasing it again. The hysteresis loop provides information about the magnetic properties and behaviour of the material.



Magnetization vs. Applied Field: The hysteresis loop illustrates how the magnetization of a material changes with the applied magnetic field. As the field increases from zero, the magnetization of the material also increases, but not linearly. The magnetization reaches saturation when further increases in the field have a negligible effect on magnetization. When the applied field is reduced, the magnetization does not immediately return to zero but follows a different path, forming a closed loop.

Magnetic Saturation: Magnetic saturation occurs when the material's magnetization reaches its maximum value and can no longer be further increased by an increase in the applied magnetic field. In the hysteresis loop, saturation is reached when the magnetization curve becomes nearly horizontal.

Remanence: Remanence, also known as residual magnetization or remanent magnetization, refers to the magnetization that remains in a material even after the applied magnetic field is reduced to zero. It represents the magnetic memory or the ability of a material to retain its magnetization. Remanence is obtained from the hysteresis loop at zero applied field.

Coercivity: Coercivity, as discussed previously, is the strength of the external magnetic field required to reduce the magnetization of a material to zero after it has been magnetized to saturation. It is related to the width of the hysteresis loop and represents the resistance of the material to demagnetization.

Energy Loss: Hysteresis in magnetic materials is associated with energy loss due to the irreversibility of magnetization changes. The area enclosed by the hysteresis loop represents the energy dissipated as heat during a complete cycle of magnetization & demagnetization.

Nano-magnetism :

Nano-magnetism refers to the study and manipulation of magnetic properties at the nanoscale, where the dimensions of the magnetic structures are typically on the order of nanometres ($1nm = 10^{-9}m$). It involves investigating the behaviour of magnetic materials, phenomena, and devices at the nanoscale level, which can exhibit unique magnetic properties and exhibit different behaviors compared to their bulk counterparts.

Properties of nano-magnetism :

1.Magnetic Nanostructures: Nano-magnetism focuses on magnetic materials and structures that have characteristic dimensions in the nanometre range. Examples of magnetic nanostructures include nanoparticles, nanowires, nanodots, thin films, and multilayers. These structures exhibit size-dependent magnetic properties and often display enhanced or modified behaviors compared to bulk materials.

2.Size and Shape Effects: At the nanoscale, the size and shape of magnetic structures significantly influence their magnetic properties. For example, reducing the size of magnetic nanoparticles can lead to changes in their magnetic anisotropy, coercivity, and magnetic relaxation dynamics. Shape anisotropy can arise in elongated structures like nanowires, influencing their magnetization reversal mechanisms.

3.Magnetic Ordering and Interactions: Nano-magnetism involves studying the magnetic ordering and interactions at the nanoscale. Magnetic materials may exhibit superparamagnetic behavior, where the magnetization direction fluctuates due to thermal effects. Magnetic interactions between nanoparticles or nanowires can give rise to collective behavior, such as magnetic coupling and spin interactions.

4.Magnetic Imaging Techniques: Various experimental techniques are used to visualize and characterize magnetic nanostructures. Scanning probe techniques like magnetic force microscopy (MFM) and scanning tunnelling microscopy (STM) enable the imaging and manipulation of individual magnetic atoms or nanostructures. X-ray and electron-based microscopy techniques provide insights into the magnetic properties and structures at high resolution.

5.Magnetic Storage and Memory: Nano-magnetism plays a crucial role in the development of magnetic storage and memory technologies. Magnetic hard drives, for instance, rely on the ability to store and retrieve information at the nanoscale using magnetic domains and nanostructured magnetic media. Spintronic devices, which utilize the spin of electrons, are also a significant area of research within nano-magnetism.

Applications: Nano-magnetism finds applications in various fields. It is employed in magnetic data storage, spintronics, magnetic sensors, biomedical applications like targeted drug delivery and magnetic hyperthermia, and emerging fields such as quantum information processing using spin qubits.

Super-paramagnetism :

Super-paramagnetism is a phenomenon observed in small magnetic particles or nanostructures, where their magnetic behavior is akin to that of individual atomic magnetic moments. It is characterized by the fluctuation of the particle's magnetization direction due to thermal effects, rather than a stable and well-defined magnetic ordering.

Properties of Super-paramagnetism :

1.Absence of Permanent Magnetization: Superparamagnetic particles do not possess a permanent magnetization in the absence of an external magnetic field. Due to thermal fluctuations, the net magnetization of the ensemble of particles averages out to zero, resulting in no overall magnetic moment.

2.Magnetic Susceptibility: Superparamagnetic materials exhibit a high magnetic susceptibility, which means they can be easily magnetized by an external magnetic field. When subjected to an applied field, the individual magnetic moments of the particles align with the field direction, resulting in a temporary magnetization.

3.Blocking Temperature: The behavior of superparamagnetic particles is strongly temperature-dependent. Above a specific temperature known as the blocking temperature (TB), thermal energy is sufficient to overcome the energy barrier associated with the alignment of magnetic moments. As a result, the particles exhibit superparamagnetic behavior and their magnetization fluctuates freely. Below the blocking temperature, the particles tend to remain magnetically aligned due to the energy barrier, displaying more conventional magnetic properties.

4.Magnetic Relaxation: Superparamagnetic particles exhibit magnetic relaxation, which refers to the time it takes for the magnetization to relax or reorient due to thermal fluctuations. The relaxation time depends on factors such as the particle size, temperature, and the energy barriers associated with the magnetic moments. Smaller particles have faster relaxation times compared to larger particles.

5.Size Dependency: The properties of superparamagnetic particles are strongly influenced by their size. As the particle size decreases, the energy barrier associated with magnetic moment alignment decreases, leading to lower blocking temperatures and faster relaxation times. This size dependence allows for tuning the magnetic behavior of superparamagnetic materials for specific applications.

6.Magnetic Hysteresis: Superparamagnetic particles do not exhibit hysteresis in their magnetization as the applied magnetic field is varied. Unlike ferromagnetic materials that display well-defined hysteresis loops, superparamagnetic materials show a reversible magnetization response that closely follows the applied field due to the absence of a stable magnetic moment.

7.Thermal Stability: The thermal stability of superparamagnetic materials refers to their ability to retain their superparamagnetic behavior at a given temperature range. Higher thermal stability means that the particles can maintain superparamagnetic characteristics at higher temperatures without transitioning to a more ordered magnetic state.

Applications :

1.Magnetic Data Storage: Superparamagnetic particles are used in magnetic recording media, such as hard disk drives. They are employed as the magnetic storage medium due to their high magnetic susceptibility and ability to switch their magnetization quickly. Superparamagnetic materials enable high-density data storage and improve the performance of magnetic storage devices.

2.Biomedical Applications: Superparamagnetic nanoparticles are extensively used in biomedical applications. They can be functionalized with various molecules to specifically target biological entities. Some key applications include:

- Magnetic Resonance Imaging (MRI): Superparamagnetic contrast agents are used in MRI to enhance image contrast and improve diagnostic accuracy. These agents, when injected into the body, create local variations in the magnetic field, resulting in enhanced imaging of specific tissues or structures.
- Drug Delivery Systems: Superparamagnetic nanoparticles can be loaded with therapeutic agents and targeted to specific sites in the body using an external magnetic field. This approach enables localized and controlled drug delivery, reducing side effects and improving treatment efficacy.
- Hyperthermia: Superparamagnetic nanoparticles can be employed in magnetic hyperthermia, a therapeutic approach for treating cancer. When exposed to an alternating magnetic field, the nanoparticles generate heat due to their rapid magnetic relaxation. This localized heating can be used to selectively destroy tumour cells while sparing healthy tissue.

3.Environmental Applications: Superparamagnetic nanoparticles are utilized in environmental applications, such as water treatment and pollutant removal. They can be functionalized to bind and remove contaminants, including heavy metals, organic pollutants, and dyes, from water or soil. Magnetic separation techniques are then employed to efficiently recover the particles along with the captured pollutants.

4.Magnetic Sensors: Superparamagnetic materials are utilized in various magnetic sensing applications. They are employed in magnetic field sensors, such as magneto resistive sensors and Hall effect sensors, which are used in navigation systems, automotive applications, and magnetic field mapping.

5.Magnetic Fluids: Superparamagnetic nanoparticles suspended in a carrier liquid form magnetic fluids or ferrofluids. These fluids exhibit unique properties, such as tuneable magnetization, high stability, and low viscosity. They are employed in applications such as mechanical seals, damping systems, and as coolants in electronic devices.

6.Fundamental Research: Superparamagnetic nanoparticles serve as model systems for studying fundamental magnetic phenomena and exploring nanoscale magnetism. They offer insights into magnetic relaxation dynamics, interactions between magnetic nanoparticles, and magnetic phase transitions at the nanoscale.