

UNIT-IV: MAGNETIC & DIELECTRIC MATERIALS

Introduction to Magnetic Materials

Magnetic materials are substances that develop a magnetic response when placed in a magnetic field. This response originates from microscopic magnetic moments associated with the electrons in atoms. These moments arise primarily from electron spin and orbital motion. When a sufficiently large number of these moments align in a particular direction, the material exhibits a measurable magnetization.

Magnetic materials are indispensable in many technologies, including transformers, motors, memory devices, magnetic sensors, and energy systems. Their behavior under an external magnetic field determines their suitability for different engineering applications.

1. Fundamental Quantities and Definitions

1.1 Magnetization (M)

Magnetization represents the magnetic dipole moment per unit volume. It reflects how strongly a material becomes magnetized when exposed to an external magnetic field. For many materials under moderate fields:

$$M = \chi H$$

where χ is the magnetic susceptibility.

1.2 Magnetic Flux (Φ)

Magnetic flux is the total magnetic field passing through a surface. It is given by:

$$\Phi = B \cdot A$$

where \mathbf{B} is the magnetic flux density and \mathbf{A} is the area.

1.3 Magnetic Flux Density (B)

Magnetic flux density quantifies the strength of the magnetic field within a material:

$$B = \frac{\Phi}{A}$$

In SI, it is measured in **tesla (T)**.

1.4 Magnetic Field Intensity (H)

The applied magnetic field is represented by \mathbf{H} , measured in A/m. The relationship among \mathbf{B} , \mathbf{H} , and \mathbf{M} is:

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

where μ_0 is the permeability of free space.

1.5 Permeability (μ)

Permeability measures how well a material supports the development of a magnetic field:

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

Two useful quantities are:

- **Absolute permeability:** μ
- **Relative permeability:**

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

Materials with high μ_r (hundreds to thousands) typically exhibit strong magnetic behavior.

1.6 Susceptibility (χ)

Susceptibility describes how easily a material can be magnetized:

- $\chi > 0 \rightarrow$ Paramagnetic
 - $\chi \ll -1 \rightarrow$ Diamagnetic
 - $\chi \gg 1 \rightarrow$ Ferromagnetic
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2. Magnetic Dipole and Dipole Moment

A magnetic dipole can be visualized as a small current loop. Its dipole moment is:

$$\mu = IA$$

where \mathbf{I} is the current and \mathbf{A} is the loop area.

Atomic-scale dipoles originate from electron spin and orbital motion. The collective alignment of such moments gives rise to the observable magnetic properties of a material.

Numerical Problems

Example 1: Magnetizing Field Calculation

A material develops a flux density of **0.004 T** and has a magnetization of **2300 A/m**. Determine the applied magnetic field intensity.

Formula:

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

Given:

- $B = 0.004 \text{ T}$
- $M = 2300 \text{ A/m}$
- $\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$

Calculation:

$$\begin{aligned}0.004 &= (4\pi \times 10^{-7})(H + 2300) \\H + 2300 &= \frac{0.004}{4\pi \times 10^{-7}} \approx 3183.1 \\H &\approx 3183.1 - 2300 = 883.1 \text{ A/m}\end{aligned}$$

Answer:

$$H \approx 883 \text{ A/m}$$

Example 2: Relative Permeability

Using the result from Example 1:

$$\begin{aligned}\mu_r &= \frac{B}{\mu_0 H} \\&= \frac{0.004}{(4\pi \times 10^{-7})(883.1)} \\&\approx 3.6\end{aligned}$$

Answer:

$$\mu_r \approx 3.6$$

Origin of Magnetic Moment

Magnetic moments in matter arise from several microscopic sources associated with particles inside an atom. The total magnetic moment of an atom is the vector sum of contributions from **electron orbital motion**, **electron spin**, and **nuclear spin**. These microscopic origins determine whether a material becomes ferromagnetic, paramagnetic, diamagnetic, or exhibits more complex magnetic behavior.

1. Electron Orbital Magnetic Moment

Electrons move in quantized orbits around the nucleus. This motion is equivalent to a small current loop, which naturally produces a magnetic dipole moment.

For an electron with orbital angular momentum \mathbf{L} , the orbital magnetic moment is:

$$\mu_L = \frac{e}{2m_e} L$$

Because the electron carries a negative charge, the direction of the orbital moment is opposite to the direction of the angular momentum.

2. Electron Spin Magnetic Moment

Electrons possess an intrinsic quantum mechanical property known as **spin**. Unlike orbital motion, electron spin is not due to physical rotation but is an inherent characteristic that produces a strong magnetic moment.

The spin magnetic moment is:

$$\mu_S = g_S \frac{e}{2m_e} S$$

where:

- S = spin angular momentum
- $g_S \approx 2$ = spin g-factor

Electron spin often contributes more to magnetism than orbital motion, especially in transition metals where orbital motion is partially quenched.

3. Nuclear Spin Magnetic Moment

The nucleus itself also possesses spin due to the collective motion of protons and neutrons. Each nucleon has its own intrinsic magnetic moment:

- Protons → positive magnetic moment
- Neutrons → small magnetic moment due to internal quark structure

The nuclear magnetic moment is given by:

$$\mu_N = g_N \frac{e}{2m_p} I$$

where:

- I = nuclear spin angular momentum
- g_N = nuclear g-factor
- m_p = proton mass

A related constant, the **nuclear magneton**, is defined as:

$$\mu_N = \frac{e\hbar}{2m_p}$$

Its value is:

$$\mu_N \approx 5.05 \times 10^{-27} \text{ A}\cdot\text{m}^2$$

This value is much smaller (roughly 1/1836) than the Bohr magneton because the proton mass is far larger than the electron mass.

Role of Nuclear Spin in Magnetism

- Nuclear spin does **not** contribute significantly to bulk magnetism (like ferromagnetism) because its magnetic moment is extremely small.
- However, it is crucial in **nuclear magnetic resonance (NMR)**, **MRI technology**, **hyperfine interactions**, and **Mössbauer spectroscopy**.

4. Total Magnetic Moment of an Atom

The total magnetic moment is a combined effect:

$$\vec{\mu}_{\text{total}} = \vec{\mu}_L + \vec{\mu}_S + \vec{\mu}_N$$

In most cases, the **electron spin** and **electron orbital** contributions dominate. Many atoms have paired electrons, cancelling orbital and spin moments; such atoms show weak or no magnetism. Atoms with unpaired electrons possess nonzero magnetic moments, which are responsible for strong magnetic behavior.

5. Bohr Magneton

The atomic unit of magnetic moment for electrons is the **Bohr magneton**:

$$\mu_B = \frac{e\hbar}{2m_e}$$
$$\mu_B \approx 9.27 \times 10^{-24} \text{ A}\cdot\text{m}^2$$

It is the reference scale for most electronic magnetic moments.

6. Numerical Problems

Example 1: Spin Magnetic Moment of an Electron

An electron has spin angular momentum:

$$S = \frac{\hbar}{2}$$
$$\mu_S = g_s \frac{e}{2m_e} S = 2 \left(\frac{e}{2m_e} \right) \left(\frac{\hbar}{2} \right)$$
$$\mu_S = \mu_B$$

Answer:

Spin magnetic moment of a free electron = **1 Bohr magneton**.

Example 2: Magnetic Moment from Nuclear Spin

A proton has nuclear spin $I = \frac{1}{2}$.

Using nuclear magneton:

$$\mu = g_p \mu_N I$$

Taking $g_p \approx 5.59$:

$$\begin{aligned}\mu &= 5.59 \times \mu_N \times \frac{1}{2} \\ \mu &\approx 2.795 \mu_N\end{aligned}$$

Answer:

Magnetic moment contributed by nuclear spin ≈ 2.8 nuclear magnetons.

Example 3: Net Moment of an Atom with Unpaired Electrons

For an atom with **4 unpaired electrons**, the approximate moment is:

$$\begin{aligned}\mu &= \sqrt{n(n+2)} \mu_B = \sqrt{4(4+2)} \mu_B \\ \mu &= \sqrt{24} \mu_B \approx 4.90 \mu_B\end{aligned}$$

Answer:

Net atomic magnetic moment $\approx 4.9 \mu_B$.

Classification of Magnetic Materials

Magnetic materials are classified according to how they respond to an externally applied magnetic field. Their response depends on the presence of unpaired electrons, the strength of magnetic interactions among atoms, and the direction in which atomic magnetic moments align.

The main categories of magnetic materials are:

1. **Diamagnetic Materials**
2. **Paramagnetic Materials**
3. **Ferromagnetic Materials**
4. **Antiferromagnetic Materials**
5. **Ferrimagnetic Materials**

Each category exhibits unique magnetic behavior and physical properties.

1. Diamagnetic Materials

Characteristics

- All electrons are paired; thus the net atomic magnetic moment is zero.
- When placed in a magnetic field, they develop a small **induced magnetic moment opposite** to the field.
- Very weak magnetic response and negative susceptibility.

Properties

- **Magnetic susceptibility (χ)**: small and negative.
- **Relative permeability (μ_r)**: slightly less than 1.
- **Magnetization disappears immediately** when the external field is removed.

Examples

- Bismuth, copper, water, silver, silicon.
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2. Paramagnetic Materials

Characteristics

- Possess **unpaired electrons**, giving them tiny permanent magnetic moments.
- In the absence of a field, these moments are randomly oriented.
- When exposed to a magnetic field, they **align partially** with the field.

Properties

- χ **positive but small**.
- μ_r **slightly greater than 1**.
- Magnetization is weak and disappears when the field is removed.
- Susceptibility decreases with increasing temperature (Curie law).

Examples

- Aluminium, platinum, manganese salts, oxygen gas.
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3. Ferromagnetic Materials

Characteristics

- Strongest form of magnetism.
- Atoms possess unpaired electrons whose magnetic moments **spontaneously align** due to strong exchange interactions.

- Materials form **magnetic domains**—regions where atomic moments are aligned in the same direction.

Key Properties

- **Very large positive susceptibility ($\chi \gg 1$).**
- **High relative permeability.**
- Exhibit **hysteresis**, meaning magnetization depends on history of the applied field.
- Have a characteristic **Curie temperature (T_c)** above which ferromagnetic behavior vanishes.

Domain Behaviour

- In absence of field → random domain orientation.
- Under an applied field → domains grow and rotate toward the field direction.

Examples

- Iron, cobalt, nickel and their alloys.
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4. Antiferromagnetic Materials

Characteristics

- Magnetic moments of atoms or ions align **in equal magnitude but opposite directions**.
- This antiparallel arrangement results in **zero net magnetic moment**.

Properties

- Magnetic susceptibility is positive but small.
- Material loses antiferromagnetic order above the **Néel temperature (T_N)**.
- Shows no macroscopic magnetization in an external field, except a very slight increase.

Examples

- Manganese oxide (MnO), nickel oxide (NiO), chromium.
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5. Ferrimagnetic Materials

Characteristics

- Have two or more magnetic sublattices with opposing alignment, **but unequal magnitudes**.
- This leads to a **non-zero net magnetic moment**, unlike antiferromagnets.

Properties

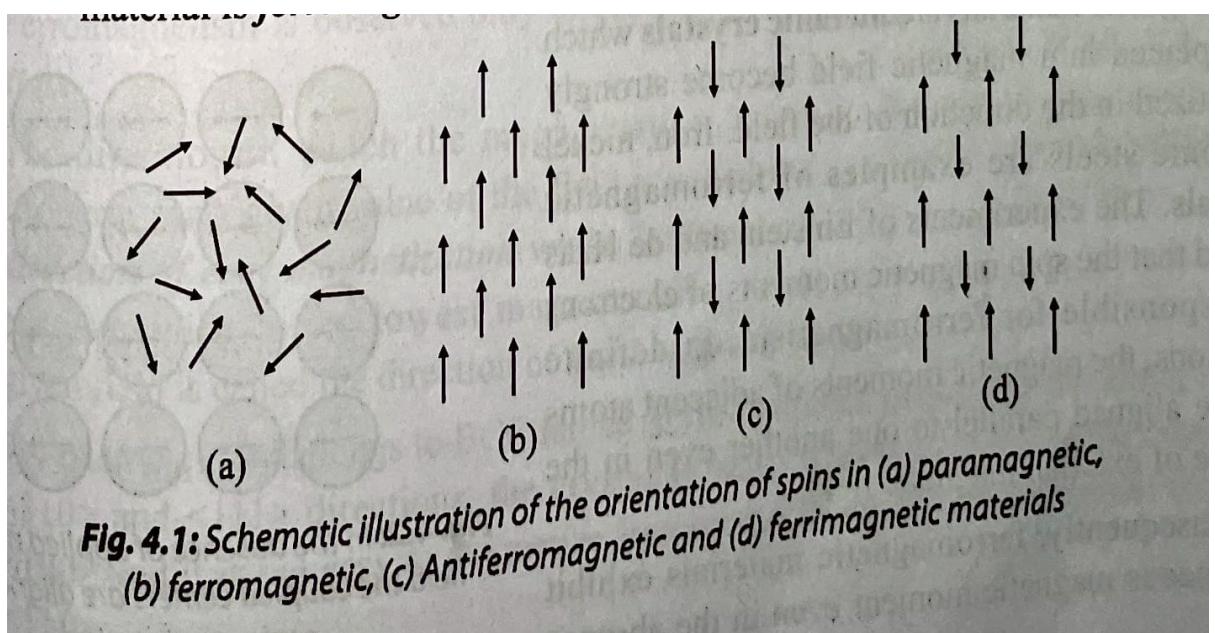
- Exhibit strong magnetization but lower than classical ferromagnets.
- Display hysteresis and domain formation.
- Have a **Curie temperature** similar to ferromagnets.

Examples

- Ferrites:
 - Magnetite (Fe_3O_4)
 - Nickel ferrite (NiFe_2O_4)
 - Zinc ferrite (ZnFe_2O_4)

Applications

- Transformer cores
- High-frequency inductors
- Microwave devices
- Magnetic recording heads



Comparison Table (Summary)

Property	Diamagnetic	Paramagnetic	Ferromagnetic	Antiferromagnetic	Ferrimagnetic
Unpaired electrons	None	Few	Many	Many	Many
Susceptibility (χ)	Negative, small	Positive, small	Very large	Small	Large
Magnetization	Opposes field	Weakly aligns	Strong alignment	Opposing equal	Opposing unequal
Hysteresis	No	No	Yes	No	Yes
Net Moment	Zero	Small	Large	Zero	Non-zero

Numerical Problems

Example 1: Estimating Magnetic Moment in a Ferrimagnet

A ferrimagnetic material has two sublattices:

- Sublattice A: $5 \mu\text{B}$
- Sublattice B: $2 \mu\text{B}$ (opposite direction)

$$\mu_{\text{net}} = \mu_A - \mu_B = 5\mu_B - 2\mu_B = 3\mu_B$$

Answer: Net magnetic moment = **$3 \mu\text{B}$.**

Example 2: Susceptibility and Permeability

A paramagnetic material has a susceptibility of:

$$\chi = 4 \times 10^{-4}$$

Find the relative permeability:

$$\mu_r = 1 + \chi = 1 + 4 \times 10^{-4} = 1.0004$$

Answer:

Relative permeability = **1.0004**

Example 3: Curie Temperature Effect

The susceptibility of a paramagnet is:

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

If $C = 0.8$ and $T = 400 K$:

$$\chi = \frac{0.8}{400} = 0.002$$

Answer:

Magnetic susceptibility = 2×10^{-3}

Hysteresis

Hysteresis is a fundamental property of ferromagnetic and ferrimagnetic materials. It describes the lag between the change in magnetization and the applied magnetic field. When a magnetic material is subjected to a complete cycle of magnetization, the magnetic response (B or M) does not follow the same path during increasing and decreasing fields. This phenomenon produces a **hysteresis loop**, which provides insight into energy loss, coercivity, retentivity, and material behavior in practical applications.

When an initially unmagnetized ferromagnetic material is exposed to an external magnetic field:

1. Magnetic domains begin to align with the applied field.
2. As the field increases, domain walls move, rotate, and reorganize.
3. When the field is removed, domains do not return to the random state.
4. The material retains some magnetization—known as **remanence** or **retentivity**.
5. A reverse magnetic field is required to bring magnetization back to zero.
6. Further reverse field drives full magnetization in the opposite direction.

Repeating this process forms a closed loop called the **B–H hysteresis loop**.

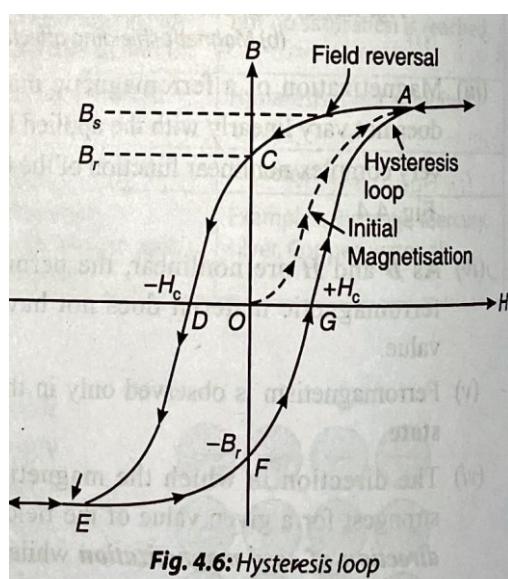


Fig. 4.6: Hysteresis loop

2.1 Initial Magnetization Curve

Starting from an unmagnetized state, the magnetization rises nonlinearly as domains rapidly align. This curve represents the first path of magnetization.

2.2 Saturation Magnetization

At high fields, nearly all domains align with the applied field, and the material reaches **saturation**. Beyond this point, further increase in field produces only small increases in B due to intrinsic atomic properties.

2.3 Remanence (Retentivity)

When the applied field is reduced to zero, the material does not demagnetize completely. The remaining magnetic flux density is called:

$$B_r = \text{remanent flux density}$$

This value represents the ability of a material to retain magnetization.

2.4 Coercivity (Coercive Field)

To reduce the magnetization to zero, a reverse field must be applied. The field required to bring the magnetic flux density to zero is known as:

$$H_c = \text{coercive field}$$

Materials with small H_c are easy to magnetize and demagnetize, whereas materials with large H_c maintain their magnetization strongly.

2.5 Saturation in Reverse Direction

Increasing the reverse field further forces domains to reorient completely in the opposite direction, reaching reverse saturation.

3. Energy Loss in the Hysteresis Loop

The **area enclosed inside the hysteresis loop** represents energy lost per unit volume during one complete magnetization cycle.

$$\text{Energy loss per cycle} \propto \text{Area of the hysteresis loop}$$

This energy loss appears as heat and is critical in devices such as transformers, inductors, and rotating machines.

- **Soft magnetic materials** → small loop area → minimal energy loss

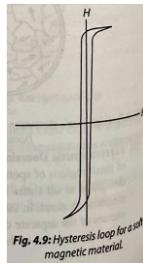
- **Hard magnetic materials** → large loop area → high energy retention

Soft and Hard Magnetic Materials

Magnetic materials are broadly classified into **soft** and **hard** types based on their hysteresis characteristics, coercivity, and ease of magnetization. Their behavior is determined by microstructure, domain-wall mobility, impurities, internal stresses, and crystal orientation.

1. Soft Magnetic Materials

Soft magnetic materials are those that can be **easily magnetized and demagnetized**. They respond quickly to changing magnetic fields and exhibit very small energy losses per cycle.



1.1 Characteristics

- **Low coercivity (H_c):** Very small reverse field required to bring magnetization to zero.
- **High permeability (μ):** Allows strong magnetization for small applied fields.
- **Low retentivity:** Do not retain significant magnetization after removal of the field.
- **Narrow hysteresis loop:** Indicates minimal energy loss.
- **High domain-wall mobility:** Domains adjust easily to external fields.

1.2 Why Soft Materials Behave This Way

- Fewer defects or impurities
- Larger grains that reduce pinning of domain walls
- Heat treatment to reduce internal stress
- Special alloying for improved electrical and magnetic properties

1.3 Examples

- Silicon steel (Fe–Si alloys)
- Soft ferrites (Mn–Zn, Ni–Zn ferrites)
- Pure iron
- Permalloy (Ni–Fe alloy)

1.4 Applications

- Transformer cores
- Inductors
- Generators and motors
- Electromagnets
- Magnetic shielding

2. Hard Magnetic Materials

Hard magnetic materials, also known as **permanent magnet materials**, are difficult to magnetize but retain magnetization strongly once magnetized.

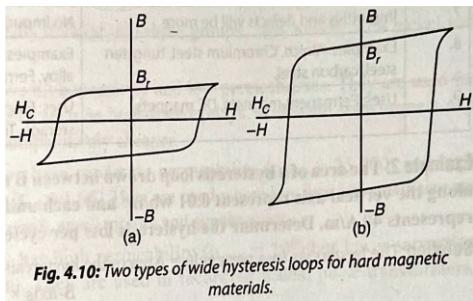


Fig. 4.10: Two types of wide hysteresis loops for hard magnetic materials.

2.1 Characteristics

- **High coercivity:** Large field required to demagnetize.
- **High remanence:** Strong ability to retain magnetic flux.
- **Wide hysteresis loop:** Indicates large energy storage capacity.
- **Low permeability:** Requires larger applied field for magnetization.
- **Stable domain structure:** Domains resist realignment even under strong opposing fields.

2.2 Why Hard Materials Behave This Way

- Strong domain-wall pinning by defects and grain boundaries
- Fine-grain microstructure with strong anisotropy
- High magnetocrystalline anisotropy energy
- Alloying elements such as Co, Al, and rare-earth elements enhance magnet rigidity

2.3 Examples

- Alnico (Al–Ni–Co alloys)
- Hard ferrites ($\text{BaFe}_{12}\text{O}_{19}$, $\text{SrFe}_{12}\text{O}_{19}$)
- Samarium–cobalt (SmCo)
- Neodymium–iron–boron (NdFeB) magnets

2.4 Applications

- Loudspeakers
- Permanent-magnet motors
- Magnetic recording media
- Sensors and actuators
- Magnetic locks and separators

Example 1: Energy Loss from Hysteresis Loop Area

A magnetic material has a hysteresis loop area equivalent to 500 J/m^3 per cycle. If a transformer core undergoes **100 cycles per second**, compute energy loss per second.

Answer:

$$\text{Energy loss per sec} = 500 \times 100 = 50,000 \text{ J/m}^3 \text{ per sec}$$

Energy loss = $5 \times 10^4 \text{ J/m}^3 \text{ per second}$.

Example 2: Soft vs Hard Material Coercivity

A soft magnetic material has coercivity $H_c = 80 \text{ A/m}$ and a hard magnetic material has $H_c = 5000 \text{ A/m}$.

Find the ratio of their coercivities.

$$\frac{H_{c,\text{hard}}}{H_{c,\text{soft}}} = \frac{5000}{80} = 62.5$$

Answer:

The hard magnetic material has **62.5 times** higher coercivity.

Example 3: Determining Remanence from Loop Data

Given a hysteresis loop where the flux density at zero field is:

$$B_r = 1.2 \text{ T}$$

This value represents the retentivity of the material.

Answer:

Retentivity (remanent flux density) = **1.2 Tesla**.

Weiss Domain Theory

Weiss Domain Theory explains why ferromagnetic materials exhibit strong magnetism even though individual atoms have randomly oriented magnetic moments in the absence of an external magnetic field. This theory, proposed by Pierre Weiss, introduces the concept of **magnetic domains**—small regions where atomic magnetic moments are spontaneously aligned.

The interaction that causes this alignment is known as the **Weiss molecular field**, an internal field much stronger than any external magnetic field applied to the material.

1. Basic Postulates of Weiss Domain Theory

Weiss proposed two foundational ideas:

1.1 Existence of Spontaneous Magnetization

Even without an external magnetic field, ferromagnetic materials contain regions where atomic magnetic moments align parallel to each other. This alignment is due to strong internal forces and results in **spontaneous magnetization**.

1.2 Division into Domains

Ferromagnetic materials are divided into small regions called **domains**.

Within each domain:

- The magnetic moments are strongly aligned.
- The alignment minimizes internal energy.
- Each domain behaves like a tiny magnet with uniform magnetization.

Domains differ in orientation, so overall the material appears unmagnetized.

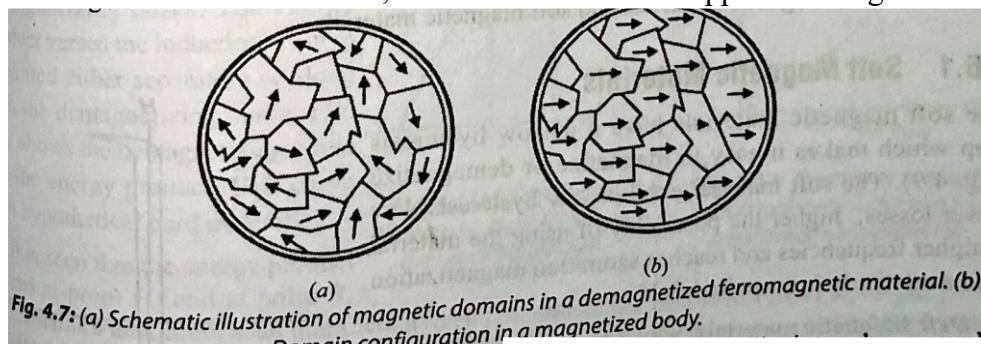


Fig. 4.7: (a) Schematic illustration of magnetic domains in a demagnetized ferromagnetic material. (b) Domain configuration in a magnetized body.

2. Weiss Molecular Field

To explain spontaneous alignment, Weiss introduced the idea of an internal field:

$$H_W = \alpha M$$

where:

- H_W = Weiss molecular field
- M = magnetization of the domain
- α = Weiss constant (positive)

The molecular field is extremely strong—often 100 to 1000 times stronger than the externally applied field. This field forces magnetic moments within a domain to align parallel to each other.

3. Domain Orientation in Absence of an External Field

In an unmagnetized ferromagnet:

- Domains exist with different magnetization directions.
- The vector sum of all domain moments is zero.
- This configuration minimizes the overall magnetic energy by reducing external stray fields.

Thus, despite strong internal alignment, the material shows **no net magnetization**.

4. Behavior of Domains Under an Applied Magnetic Field

When an external magnetic field is applied, the domain structure undergoes transformations:

4.1 Domain Wall Motion

Domains aligned with the field grow at the expense of others. This happens through movement of **domain walls**, the boundaries separating regions of different orientation.

4.2 Domain Rotation

At higher fields, entire domains rotate to align more closely with the external field.

4.3 Single-Domain State at Saturation

When saturation is reached:

- All domains align with the field
- The material behaves as one large domain

Removing the field causes domains to partially return, resulting in **remanent magnetization**.

5. Energies Influencing Domain Formation

Several energies determine domain size and structure:

5.1 Exchange Energy

Favors parallel alignment of spins.

5.2 Magnetostatic Energy

Favors formation of multiple domains to reduce external magnetic fields.

5.3 Anisotropy Energy

Causes spins to align along certain crystallographic directions (easy axes).

5.4 Domain Wall Energy

Energy required to create walls between domains.

A balance of these energies leads to stable domain structures.

6. Domain Walls

Domain walls are thin transition regions where spins gradually rotate from one direction to another.

There are two major types:

1. **Bloch walls** – common in bulk materials
2. **Néel walls** – occur in thin films

Domain wall thickness and energy depend on the material's exchange and anisotropy parameters.

7. Numerical Problems

Example 1: Molecular Field Calculation

A ferromagnetic material has magnetization

$$M = 5 \times 10^5 \text{ A/m}$$

and Weiss constant

$$\alpha = 1.2 \times 10^{-3}$$

Calculate the molecular field.

$$H_W = \alpha M = (1.2 \times 10^{-3})(5 \times 10^5)$$
$$H_W = 600 \text{ A/m}$$

Answer:

Weiss molecular field = **600 A/m**

Example 2: Domain Wall Energy Estimation

Domain wall energy per unit area:

$$\gamma = 4\sqrt{AK}$$

Given:

- Exchange constant $A = 1.5 \times 10^{-11} \text{ J/m}$
- Anisotropy constant $K = 3.2 \times 10^4 \text{ J/m}^3$

$$\gamma = 4\sqrt{(1.5 \times 10^{-11})(3.2 \times 10^4)}$$
$$\gamma = 4\sqrt{4.8 \times 10^{-7}} \approx 4(6.93 \times 10^{-4})$$
$$\gamma \approx 2.77 \times 10^{-3} \text{ J/m}^2$$

Answer:

Domain wall energy $\approx 2.8 \times 10^{-3} \text{ J/m}^2$

Synthesis of Magnetic Materials Using the Sol–Gel Method

The **sol–gel method** is a widely used chemical route for synthesizing magnetic oxides, especially ferrites, nanoscale magnetic powders, thin films, and coatings. It offers excellent compositional uniformity, low-temperature processing, and precise control over microstructure. Because of these advantages, it is commonly used to prepare materials such as NiFe_2O_4 , ZnFe_2O_4 , CoFe_2O_4 , and various doped magnetic nanomaterials.

1. Principle of the Sol–Gel Process

The sol–gel technique is based on transforming a **colloidal solution (sol)** into a **three-dimensional interconnected oxide network (gel)** through controlled hydrolysis and condensation of metal precursors.

Key Chemical Steps:

1. Hydrolysis

Metal alkoxides or metal salts react with water to form hydroxylated species.

2. Condensation

Hydroxyl groups bond together to form a metal–oxygen–metal network ($M-O-M$), creating polymeric chains or clusters.

3. Gelation

Progressive condensation produces a wet gel containing a continuous solid network filled with solvent.

4. Drying

Removal of solvent leads to a xerogel.

5. Calcination / Sintering

Heat treatment produces the final crystalline magnetic oxide.

2. Materials Used

- **Metal alkoxides** (rare, expensive)
- **Metal nitrates or chlorides** (common and highly used for ferrites)
- **Chelating agents** such as citric acid, ethylene glycol, or acetic acid
- **Solvents**: water or alcohol
- **pH adjusters**: ammonia, citric acid, or nitric acid

The choice of precursor strongly influences particle size and crystallinity.

3. General Procedure for Sol–Gel Synthesis of Magnetic Oxides

Step 1: Preparation of the Sol

- Dissolve metal salts (e.g., Fe^{3+} , Ni^{2+} , Co^{2+} , Zn^{2+}) in distilled water or alcohol.
- Add a complexing agent such as citric acid or ethylene glycol.
- Maintain stirring for homogeneous mixing.
- Adjust the pH to promote hydrolysis and chelation.

Step 2: Formation of the Gel

- Gentle heating promotes condensation reactions.
- Viscosity increases until a gel-like network forms.
- Gelation indicates formation of polymeric $M-O-M$ chains.

Step 3: Drying the Gel

- The wet gel is dried at moderate temperature (80–120°C).
- Solvent evaporation converts the gel into a porous xerogel.

Step 4: Calcination

- The dried gel is heated (300–800°C depending on the material).
- Organic residues burn off.
- Crystalline magnetic phases (such as spinel ferrites) form.

Step 5: Grinding and Final Processing

- The calcined powder is ground to remove agglomerates.
 - For thin films, the sol can be directly deposited on substrates before gelation.
-

4. Advantages of Sol–Gel Method

- Produces extremely **uniform composition**
- Low synthesis temperature compared to solid-state routes
- Enabled synthesis of **nano-sized** magnetic particles
- High purity and excellent chemical homogeneity
- Suitable for bulk powders, thin films, fibers, and coatings

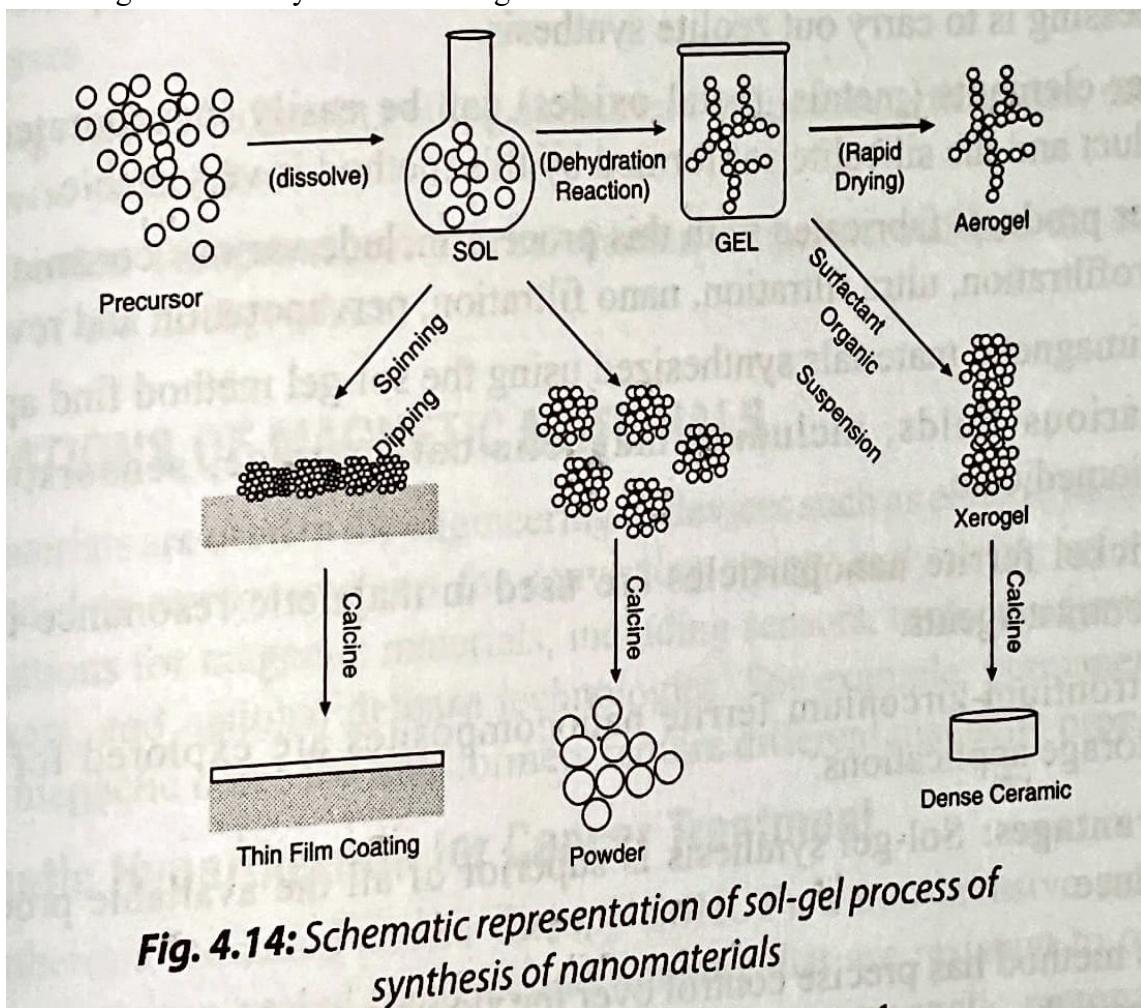
- Allows fine control of **microstructure**, **stoichiometry**, and **particle size**

5. Limitations

- Requires careful control of pH, temperature, and precursor ratios
- Drying may cause cracking or shrinkage in gels
- Some metal alkoxides are expensive or sensitive to moisture
- Risk of agglomeration during calcination

6. Applications

- Magnetic nanoparticles for biomedical uses
- Ferrite cores for high-frequency devices
- Catalysts
- Magnetic sensors
- Coatings for electromagnetic shielding
- Magnetic memory and data storage materials



Magnetic Hyperthermia for Cancer Treatment

Magnetic hyperthermia is an advanced therapeutic technique in which **magnetic nanoparticles** are used to selectively heat and destroy cancer cells. The method exploits the ability of certain magnetic materials—typically ferrimagnetic or superparamagnetic nanoparticles—to generate heat when exposed to an **alternating magnetic field (AMF)**.

Because tumor cells are more sensitive to elevated temperatures than healthy cells, controlled heating can induce apoptosis or necrosis in cancerous tissues.

1. Principle of Magnetic Hyperthermia

The central idea behind magnetic hyperthermia is to raise the temperature of the tumor region to approximately **42–46°C**. This range is sufficient to damage cancer cells while minimizing harm to surrounding healthy tissue.

Heat Generation Mechanisms

When magnetic nanoparticles are subjected to an AC magnetic field, heat is produced through:

1. **Néel Relaxation**
 - Reorientation of magnetic moments within a particle generates thermal energy.
2. **Brownian Relaxation**
 - Physical rotation of the nanoparticles in the medium produces heat.
3. **Hysteresis Losses**
 - For ferrimagnetic particles, the area of the hysteresis loop under AC excitation contributes to heat production.

The total heating power is often quantified using the **Specific Absorption Rate (SAR)**, measured in W/g.

2. Magnetic Nanoparticles Used

The nanoparticles used must be biocompatible, chemically stable, and capable of strong heating under an alternating magnetic field.

Common Materials

- **Superparamagnetic iron oxide nanoparticles (SPIONs)**
 - Fe₃O₄ (magnetite)
 - γ-Fe₂O₃ (maghemite)
- **Doped ferrites**
 - MnFe₂O₄, CoFe₂O₄, ZnFe₂O₄
- **Surface-functionalized nanoparticles**
 - Coated with dextran, PEG, silica, or polymers to enhance circulation time and reduce toxicity.

Nanoparticle size typically ranges from **5–30 nm** for optimal heating and biological compatibility.

3. Procedure of Magnetic Hyperthermia

Step 1: Targeted Delivery

Nanoparticles are delivered to the tumor through:

- Direct injection
- Intravenous administration with surface ligands (antibodies, peptides) for tumor targeting

Step 2: Application of Alternating Magnetic Field

An AMF with frequencies typically between **100–500 kHz** is applied.

Step 3: Heat Generation in Tumor

Nanoparticles absorb magnetic energy and convert it to heat through relaxation and hysteresis losses.

Step 4: Cancer Cell Destruction

- Tumor temperature rises to therapeutic hyperthermia range.
- Cancer cells undergo:
 - Protein denaturation
 - Membrane disruption
 - Metabolic failure
 - Apoptosis or necrosis

4. Advantages of Magnetic Hyperthermia

- **Localized treatment:** Heat is generated only where nanoparticles accumulate.
- **Minimally invasive:** Does not require major surgery.
- **Reduced systemic toxicity:** Unlike chemotherapy, it targets specific regions.
- **Compatible with combination therapies:**
 - Chemotherapy
 - Radiotherapy
 - Immunotherapy
- **Suitable for deep-seated tumors** (liver, brain, prostate) due to deep penetration of magnetic fields.

5. Challenges and Limitations

- Controlled delivery of nanoparticles to tumors remains complex.
- Uneven distribution may lead to insufficient heating.
- Excessive heat may risk local tissue damage if not precisely monitored.
- Long-term biocompatibility and clearance from the body must be ensured.

Magnets for Electric Vehicles (EVs)

Magnets play a crucial role in the performance, efficiency, and reliability of electric vehicles. They form the core of electric motors that convert electrical energy into mechanical motion. The choice of magnet material directly impacts torque density, power output, motor size, thermal resistance, and overall energy consumption.

Modern EVs predominantly use **permanent magnet synchronous motors (PMSMs)**, which rely on high-performance rare-earth magnets due to their exceptional magnetic properties.

1. Requirements of Magnets in EV Motors

Electric vehicle traction motors require magnets with the following characteristics:

1. High Magnetic Strength

A strong magnetic field enables high torque and high power density.

2. High Coercivity

The magnet must resist demagnetization, especially under:

- Elevated temperatures
- Strong opposing magnetic fields during operation

3. Thermal Stability

EV motors can reach **150–200°C**, so magnets must maintain performance at high temperatures.

4. Mechanical Durability

Magnets must withstand:

- Vibration
- Shock
- Repeated thermal cycling

5. Corrosion Resistance

Coatings or surface treatments (nickel, epoxy) are applied to prevent degradation.

2. Types of Magnets Used in EV Motors

2.1 Neodymium–Iron–Boron (NdFeB) Magnets

These are the most widely used magnets in EV motors.

Key Features:

- Extremely high energy product (up to 440 kJ/m³)
- High remanence and coercivity
- Excellent power density
- Can be engineered to withstand high temperatures (Grade N35–N52, or high-temp grades like H, SH, UH)

Advantages:

- Compact motor design
- High efficiency
- High torque at low speeds

Limitation:

- Expensive due to rare-earth elements
 - Sensitive to high temperatures without special doping (e.g., Dysprosium addition)
-

2.2 Samarium–Cobalt (SmCo) Magnets

Key Features:

- Outstanding thermal stability (up to 300–350°C)
- High corrosion resistance
- High coercivity

Advantages:

- Ideal for high-temperature motors
- More stable than NdFeB in harsh environments

Limitations:

- Expensive
 - Lower energy product compared to NdFeB
-

2.3 Ferrite (Ceramic) Magnets

Key Features:

- Low cost
- Good corrosion resistance
- High resistivity (reduces eddy current losses)

Advantages:

- Economical
- Useful in auxiliary motors

Limitations:

- Low magnetic strength
- Not suitable for high-power traction motors

3. Why EVs Prefer Rare-Earth Magnets

EV motors aim for high efficiency and compact design. Rare-earth magnets provide:

- High torque density
- Reduced motor weight
- High power-to-volume ratio
- Low electrical consumption
- Smooth acceleration and regenerative braking performance

Because of these advantages, NdFeB-based PMSMs are used in most modern electric cars.

4. Magnet Placement in EV Motors

Permanent magnets are strategically embedded into the rotor. Key designs include:

4.1 Surface-mounted PMSM

- Magnets placed on the rotor surface
- High efficiency but lower mechanical strength

4.2 Interior PMSM (IPM)

- Magnets buried inside the rotor
- Increased mechanical robustness
- High reluctance torque
- Widely used in modern EVs (e.g., Tesla, Nissan)

5. Advantages of Permanent Magnet Motors for EVs

- High efficiency (92–97%)
- Compact design
- High torque at low speeds
- Lower heating losses
- High power density
- Smooth operation

6. Challenges in Magnet Use for EVs

- Rising cost of rare-earth elements
- Supply chain dependency
- Thermal demagnetization risk
- Need for robust coatings and stabilization

Research is ongoing to develop:

- Dysprosium-free high-temperature magnets
- Recycled rare-earth magnets
- Hybrid motor designs (PM + reluctance motor)

Giant Magneto-Resistance (GMR)

Giant Magneto-Resistance (GMR) is a quantum mechanical phenomenon observed in multilayer structures composed of alternating **ferromagnetic** and **non-magnetic conductive** layers. When an electric current flows through such a structure, the electrical resistance changes significantly depending on the **relative alignment** of the magnetic layers.

This effect is much stronger than conventional magnetoresistance and is widely used in ultra-sensitive magnetic sensors, hard-disk read heads, biosensors, and spintronic devices.

1. Principle of GMR

A typical GMR structure consists of:

- Two ferromagnetic layers (e.g., Fe, Co, NiFe)
- Separated by a thin non-magnetic metallic layer (e.g., Cu, Ag, Au)

The resistance depends on whether the magnetic layers are:

1.1 Parallel Alignment

- Magnetic moments of the layers point in the same direction
- Electron spins with matching orientation can travel easily
- **Lower scattering, lower resistance**

1.2 Antiparallel Alignment

- Magnetic moments point in opposite directions
- Electrons experience increased scattering
- **Higher resistance**

This dramatic change in resistance is called **Giant Magneto-Resistance**.

2. Origin of the GMR Effect

GMR arises due to **spin-dependent electron scattering**, meaning electrons with different spin orientations experience different resistances when passing through magnetic layers.

Key ideas:

- Conduction electrons are spin-polarized.
 - Scattering probability depends on the relative spin direction of electrons and magnetic moments.
 - Thin non-magnetic layers allow electrons to maintain spin coherence.
 - Switching of magnetic layers between parallel and antiparallel states changes overall resistance.
-

3. Types of GMR Structures

3.1 Multilayer GMR

Repeating stacks of FM/NM/FM layers.

Strong GMR ratio, used in early research and development.

3.2 Spin-Valve GMR

Most important for practical devices.

Structure:

- One ferromagnetic layer is **pinned** (its magnetization fixed)
- The other is **free** (switches easily)

Resistance changes sharply with applied magnetic field.

3.3 Granular GMR

Magnetic nanoparticles dispersed in a non-magnetic matrix.

4. Working of a GMR Device

A GMR sensor typically contains:

- A **pinned magnetic layer** (set using an antiferromagnetic layer such as FeMn)
- A **non-magnetic spacer layer**
- A **free magnetic layer**

Operation:

1. An applied magnetic field changes the direction of the **free layer**.
 2. The pinned layer remains fixed.
 3. The relative orientation determines resistance:
 - o Parallel → low resistance
 - o Antiparallel → high resistance
 4. A small current passing through the structure produces a measurable voltage change.
- This sensitivity makes GMR sensors capable of detecting very small magnetic fields.
-

5. Applications of GMR

5.1 Data Storage (Hard Disk Read Heads)

- The first large-scale use of GMR.
- Detects magnetic bits on the disk by converting small field changes into resistance changes.

5.2 Automotive Sensors

- Wheel speed (ABS sensors)
- Position and angle sensors

5.3 Biomedical Sensors

- Detect magnetic nanoparticles for imaging and diagnostics.

5.4 Magnetic Field Sensors

- Compass modules
- Non-contact current sensors

5.5 Spintronic Devices

- MRAM (Magnetoresistive Random Access Memory)
 - Logic devices
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6. Advantages of GMR Technology

- Extremely high sensitivity
 - Low power consumption
 - Miniaturization possible
 - High signal-to-noise ratio
 - Linear response in certain device designs
-

7. Limitations

- Temperature sensitivity
- Thin-film fabrication complexity
- Requires precise control of layer thickness