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Critical Study of Ferromagnetic Materials

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Abstract – Magnetic materials play significant role in developing science and technology. Due to their innovative features and applications in different fields, magnetic nanoparticles are in high demand recently. Due to their promising applications in various fields like electronics, optics, ceramics, high-density magnetic storage devices, tumour-targeted drug delivery systems, contrast enhancers for magnetic resonance imaging, transformer cores, catalysis, biomedicine, etc., spinel ferrite nanoparticles attract significant interest. This paper reflects critical study of Ferromagnetic materials.

Key Words – Ferromagnetic, Technology, Electronics, Nanoparticles

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1.1 INTRODUCTION

Magnetic materials play an important role in the development of science and technology. Due to their innovative features and wide applications in different fields, magnetic nanoparticles have been in high demand in recent years. Among these, due to their promising applications in various fields such as electronics, optics, ceramics, high-density magnetic storage devices, tumour-targeted drug delivery systems, contrast enhancers for magnetic resonance imaging, transformer cores, catalysis, biomedicine, etc., spinel ferrite nanoparticles attract significant interest. The discovery of new materials, the process of synthesis and the development of new theoretical and experimental research techniques that provide opportunities for novel nano devices and nanomaterials to be produced. It is -important to understand their intrinsic features in order to design nanomaterials and Nano devices for the next decade. Many researchers are working around the world to create nanomaterials that are engineered to perform more complex and successful tasks. The creation of entirely new technologies and nanomaterials with desirable functional properties will therefore lead to a generation of new products that in the near future will increase the quality of the living environment.

Materials that are smaller than 100nm in grain size are known as nanomaterials. These materials have structural properties that lie between those of atoms and bulk materials. Due to their new characteristics on the Nano scale, magnetic nanoparticles have recently become the subject of intense research. The properties of nanomaterials vary significantly from those of atoms and bulk materials. This is due to the small particle size that makes them

1. Reduced imperfections
2. Quantum confinement
3. Large fraction of surface atoms

Nanomaterials have a vast surface area to volume ratio (S/V) due to their small dimensions, which allows the material's large fraction of atoms to be on the surface, resulting in more material properties depending on the surface [1, 2]. Quantum confinement has significant effects on nanomaterial properties. The density of the charge carriers and the composition of the energy band in the nanomaterial are very different from their bulk material equivalents, and this, in turn, will affect the material's physical and chemical characteristics. Reduced imperfections are also a crucial factor in determining nanomaterial properties. Nanomaterials facilitate a process of self-purification in which the imperfections and impurities of the intrinsic material can enter the surface during the sintering process. The intrinsic properties of the nanomaterial [3] are influenced by this improved material perfection.

In the case of bulk materials, rather than their size and form, their intrinsic magnetic properties such as saturation magnetization (MS), coercive force (HC) and Curie temperature (TC) depend on the chemical composition and crystallographic structure. There are a wide range of unusual magnetic properties in magnetic nanoparticles, such as super para magnetism, increased coercivity, magnetic quantum tunnelling [4, 5], etc. The finite-size and surface effects of these magnetic characteristics of the nanomaterial are significantly affected [6]. While several attempts have continued over the last few decades, a clear understanding of the relationship between the physical characteristics of ferrite materials and the atomic-scale structural parameters is necessary for the Nano regime. For the design of complex electromagnetic characteristics, the processing of Nano ferrite spinel particles is of great importance. Nano ferrite particles have multitudinous applications due to these peculiar features. Polycrystalline ferrites also exhibit dielectric behaviour in addition to magnetic properties, which makes them ideal for high-frequency applications (microwave and radio frequencies) [7-10]. It is therefore necessary to study, at different frequencies, the dielectric properties of Nano ferrites. Detailed knowledge of the effect of dopant concentration on ferrite dielectric behavior can be useful for the manufacture of ferrites with tenable dielectric properties, which is very useful for practical applications.

1.2 CLASSIFICATION OF MAGNETIC MATERIALS

Magnetic materials have been divided into five groups based on the existence of the interaction with the external applied magnetic field.

1. Diamagnetic materials
2. Paramagnetic materials
3. Ferromagnetic materials
4. Antiferromagnetic materials
5. Ferromagnetic materials

a) Diamagnetic materials

Diamagnetism is a magnetism that is weak and the fundamental property of all matter[19]. It is mainly due to the orbital electrons' non-cooperative reaction under the external magnetic field applied. The substance acquires weak magnetism in the direction opposite to the direction of the applied field when an external magnetic field is applied. It is the product of changes in electrons' orbital motion. Bismuth, zinc, copper, gold, silver, lead, mercury, etc. Examples:.

b) Paramagnetic materials

Paramagnetic materials, even in the absence of an applied field, have permanent magnetic moments. It arises due to the presence in the atomic orbital of one or more unpaired electrons. In pure paramagnetic compounds, in the absence of an external field, the atomic magnetic moments are randomly aligned and do not interfere with each other, resulting in zero net magnetic moments. This magnetic field tends to transform the unfavourably focused magnetic moments in the direction of the applied field when the external magnetic field is applied. In the absence of an externally applied magnetic field, paramagnetic materials do not maintain any magnetisation. Examples: aluminium, copper chloride, manganese, platinum, etc.

c) Ferromagnetic Materials

The material is a ferromagnetic material if the interaction between the nearby magnetic moments is strong in such a way that all the magnetic moments match in parallel. Even in the absence of an outside magnetic field, a ferromagnetic substance possesses a net magnetic moment. -Iron, cobalt, nickel, etc. Examples:

d) Antiferromagnetic Materials

When the separation between the atoms is minimal in some materials, the exchange coupling induces between adjacent magnetic moments, causing the magnetic moments to orient in an anti-parallel direction. The adjacent magnetic moments in these substances are identical and anti-parallel in direction, thus removing the resulting magnetization. Neel temperature (TN) is the most characteristic attribute of the anti-ferromagnetic substance. The temperature above which an anti-ferromagnetic material becomes paramagnetic is known as Neel temperature (TN). Chromium (Cr) is the only element in the periodic table that exhibits anti-ferromagnetic behaviour at room temperature. Examples: - Cr, NiO, Fe_2O_3, etc.

e) Ferromagnetic Materials

Neel (1948) first coined the term ferrimagnetism to describe the properties of certain materials that show spontaneous magnetization below a certain temperature, resulting from the anti-parallel alignment of atomic magnetic moments. Magnetic moments are not equal in certain materials and are aligned anti-parallel to each other in such a way that there is a net magnetic moment, and such materials are said to be ferromagnetic. Examples: - The arrangement of magnetic moments by ferrites plays an important role in differentiating the various forms of magnetism present in the materials (Fig. 1.1).

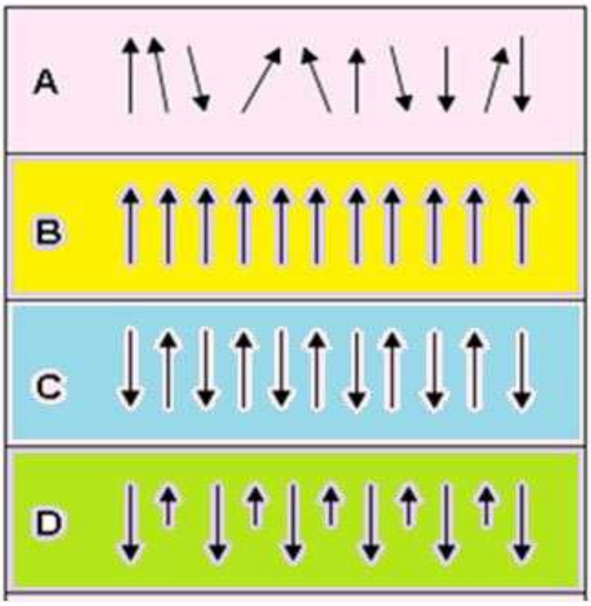

Fig.1.1 Types of magnetism: (A) Para (B) Ferro (C) Antiferro and (D) Ferrimagnetism

1.3 CLASSIFICATION OF FERRITES

1.3.1 Classification Based on Crystal Structure

Ferrites are ferromagnetic materials consisting of iron oxide as their main components. Based on the crystal structure ferrites are classified into four types, as described below:

1. Spinel ferrites (or) cubic ferrites
2. Garnets
3. Magnetoplumbite (or) Hexagonal ferrites
4. Orthoferrites

Table 1.1: Classification of Ferrites

Ferrite Type	Structure	General formula	Example
Spinel	Cubic	Me2O4	M = Ni, MN, Co, Cu, Mg, Zn e.g., Cu Fe2O4
Garnet	Cubic	3R2O3.5 Fe2O3	R = Dee, God, Ho, PR, By Y, Ms., Au, Err, Lu e.g.,3Y2O3.5Fe2O3
Magnetoplumbite	Hexagonal	Me12O19	M = Ba, Sir, Pub, CA e.g., BaO.6Fe2O3
Orthoferrites	Perovskite	RFeO3	Dee, Err, Y, By R is rare earth

i. Spinel Ferrites

Spinel ferrites are an important class of magnetic materials having the general chemical formula AB2O4, where A represents metal caption with +2 valence such as MN^{2+}, Co^{2+}, Ni^{2+}, Cu^{2+}, Zn^{2+}, Mg^{2+}, etc. and B is the trivalent iron action (Fe^{3+}). A can be replaced by divalent captions whereas Fe^{3+} can be replaced by trivalent captions like Cr^{3+}, Al^{3+}, GA^{3+}, etc. They have a crystal structure identical to naturally occurring mineral spinel (Gal2O4). Therefore, as mentioned above the ferrites with AB2O4 structure are called as spinel ferrites or simply spinel.

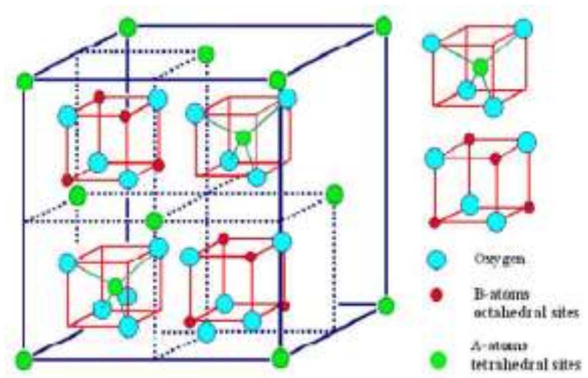

Fig. 1.2 Crystal structure of spinel ferrite

In a cubic structure, Spinel ferrites crystallise. These ferrites are, thus, also called cubic ferrites. The arrangement of spinel ferrites is shown in Fig.1.2. A close-packed oxygen anion structure is composed of the spinel lattice in which 32 O^{2-} ions form the unit cell. These O^{2-} anions are packed in the FCC arrangement leaving two types neighboring oxygen anions while the other is the octahedral (B) site surrounded by six nearest oxygen anions. There are total 64 A-sites and 32 B-sites present in the unit cell, out of which only 8 A-sites and 16 B-sites are occupied by metal captions to maintain charge neutrality in the crystal. Therefore, the unit cell of spinel ferrite contains eight molecules (8 formula units MFe2O4). 8 Me2O4 = (8M + 16Fe) Metal captions + 32 Oxygen anions = 56 ions.

The distribution of captions between octahedral (B) and tetrahedral (A) sites can affect many factors, such as chemical composition, ionic radius, electronic structure, electrostatic energy, preparation method and conditions of preparation.

Spinel ferrites can be categorized into three groups based on the caption distribution over two primary sites (i.e. A and B sites).

a) Normal spinel ferrites

b) Inverse spinel ferrites and

c) Random spinel ferrites

a) Normal spinel ferrites

Spinels are referred to as regular spinel ferrites with only divalent metal captions in the tetrahedral sites (A sites) and trivalent captions at octahedral sites (B sites).

Normal spinel's have the general formula: $(M^{2+})_A[Me^{3+}{}_2]_B O_4$

Where 'M' represents divalent captions and 'Me' for trivalent captions

b) Inverse spinel ferrites

In the case of inverse spinel ferrites, the divalent metal captions (M^2+) and half of the trivalent captions (Me^3+) residing in the octahedral sites, whereas the other half of the Me^3+ metal captions occupy the tetrahedral sites.

Inverse spinel's have represented by the general formula: $(Me^{3+})_A[M^{2+}Me^{3+}]_B O_4$

c) Random spinel ferrites

The divalent and trivalent metal ions were randomly distributed over the interstitial sites of both the tetrahedral (A-site) and octahedral (B-site) in certain ferrites. These ferrites are known as spinel ferrites at random. The random spinel ferrite structure $(M^{2+}{}_{\delta}Me^{3+}{}_{1-\delta})_A[M^{2+}{}_{1-\delta}Me^{3+}{}_{1+\delta}]_B O_4$ is represented by the general formula Of the Reversal. It's also called the parameter of distribution. The method of preparation and chemical composition of ferrites depends on it.

The three different types of panel ferrites are defined as depending upon the values of the distribution parameter δ.

δ = 1 normal spinel ferrite,

δ = 0 inverse spinel ferrite,

0 < δ < 1 random spinel ferrite.

Table 1.2: Classification of Spinel Ferrites

Ferrite Type	General formula	Example
Normal spinel	$(M^{2+})_A[Me^{3+}{}_2]_B O_4$	Zn Fe2O4, Cd Fe2O4
Inverse spinel	$(Me^{3+})_A[M^{2+}Me^{3+}]_B O_4$	Ni Fe2O4, CoFe2O4, Fe3O4
Random spinel	$(M^{2+}{}_{\delta}Me^{3+}{}_{1-\delta})_A[M^{2+}{}_{1-\delta}\ Me^{3+}{}_{1+\delta}]_B O_4$ $(0 < \delta < 1)$	MgFe O ,MnFe O, CuFe2O4

ii. Garnets

The rare earth garnets have the chemical formula $R_3Fe_5O_{12}$ or $3R_2O_3.5\ Fe_2O_3$ where, R is the Yttrium (Y) or rare earth ions such as Dee, Ho, God, PR, by, etc. The garnet's crystal form is cubic. Three interstitial sites are composed of rare earth garnets, namely dodecahedral (a), octahedral (c) and tetrahedral (d). Garnets have a complex arrangement of crystals, and in magneto-optical applications these are commonly used.

iii. Hexagonal ferrites

The third group of ferrites is the Hexagonal ferrites having the general chemical formula $Me_{12}O_{19}$ or Meow. 6 Fe_2O_3, where M can be Pub, Sir or Ba. Hexagonal ferrites have three different interstitial sites i.e. tetrahedral, original pyramid and octahedral sites. The hexagonal ferrites' crystal structure is highly complex. Owing to their inherent magnetic properties such as high saturation magnetization (MS) and coercive magnetisation, these are used as permanent magnets. (HC). Barium ferrite ($Balfe_{12}O_{19}$) and Strontium ferrite ($Surfed_{12}O_{19}$) are the good examples of hexagonal ferrites, and these are widely used in microwave device applications.

iv) Orthoferrites

The general chemical composition of orthoferrites is Freon3, where R represents various rare-earth elements such as How, Dee, Err, Y, by, etc. Orthoferrites are transparent magnetic materials that can, under the influence of a magnetic field, change the polarization of a light beam. In optical communication techniques, this property makes them theoretically useful as sensors and actuators.

1.4.2 Classification Based on Magnetization

Based on the persistence of their magnetization, ferrites are classified into two types [30]:

a. Soft Ferrites.

b. Hard Ferrites.

i) Soft ferrites

Ferrites which are easily magnetized and demagnetized are known as soft ferrites. They have characterized by narrow hysteresis loop (Fig. 1.3). Examples: - Iron-silicon alloy, Ni–Fe (perm alloy), MN–Zn ferrite, Ni–Zn ferrite, etc.

ii) Hard Ferrites

Ferrites, which are called strong ferrites, have a high resistance to magnetization and demagnetization. They were characterized by large loops of hysteresis (Fig. 1.4). Examples: - Strontium ferrite ($Surfed_{12}O_{19}$), Barium ferrite (Ba $Fe_{12}O_{19}$), Cobalt ferrite ($Coffee_2O_4$), etc.

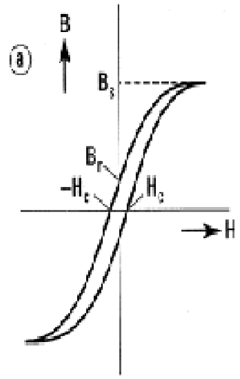

Fig 1.3 Soft ferrites

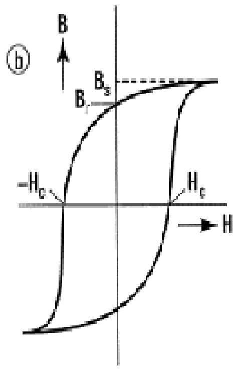

Fig 1.4 Hard ferrites

Table 1.3: Characteristics of Ferrites

Soft Ferrites	Hard Ferrites
Hysteresis loop area is narrow	Hysteresis loop area is broad
Low hysteresis loss	More hysteresis loss
The retentively and coercively values are small	The retentively and coercively values are high
The permeability and susceptibility values are high	The permeability and susceptibility values are small
They are used to make electromagnets	They are used to make permanent magnets
Low magneto crystalline anisotropy	High magneto crystalline anisotropy
Applications: In electromagnetic machines Recording heads/P Transformers in T.V. sets Transformer cores Inductors Microwave equipment Switching equipment Data storage matrix	**Applications:** Magnetic detectors noisy speakers Microphones Flux meters aping devices Magnetic separators Permanent magnet preparation Voltage regulators Magnetic detectors loud speakers Magnetic detectors loud speakers

1.5 APPLICATIONS OF FERRITES

The ceramic magnetic materials that include iron oxide as a primary component are ferrites. Due to their combined twin features of the electrical insulator and magnetic conductor, they have a large range of applications. Ferrite exhibits high specific power, low losses of dielectric and eddy current, high permeability, high magnetization of saturation, Curie temperature, high chemical stability, etc. These are the properties that make the ferrites indispensable in the application of radio contact and television. As cores for inducers and transformers, they have found wide-spread application. The characteristics that have made ferrites so useful for microwave frequencies on radio and television frequencies also provide the key to their use. Microwave machines such as switches, circulators, modulators, phase shifters, limiters, ferrite-magnetic material isolators. Soft ferrites have recently become attractive for their applications in microwave systems, rod antennas, radio frequency circuits, transformer cores, high-quality filters, inductors, noise filters, high-speed digital tape read/write heads, memory cores, high-density data storage, gas sensors, magnetic sensors, chemical sensors, high-resistivity catalysts, low magnetic, high-density data storage, gas sensors

Low coercive, low eddy current losses and high resistivity values replaced mixed ferrite materials commonly used in radio, TV, radar, audio-video and digital imaging, bubble devices, and computer memory cores. For good output in the application, low loss polycrystalline ferrites should be used in a high-frequency range. In the automotive industry and, most recently, in electric cars, another strong application for ferrite materials lies. Ferrite materials are also important for EMI applications. In the frequency range of MHz, spinel ferrites perform very well as thin impedance matched absorbers and are commonly used for TV ghost suppression and anechoic chambers. The use of small and portable power supplies for computers and microprocessors has also resulted in increased demand for high switching frequency ferrites and improved performance of the material. The new applications are growing rapidly in the area of information technology and microwave engineering. A huge demand for high-quality ferrites for transformer cores, power supplies, deflection yokes, data storage devices, recording, and interface suppression has been generated by research projects in these domains.

A renewed interest in the analysis of nano sized ferrites with possible applications in modern science and technology has recently been expressed. The quest for new products with novel or improved functionality and a fundamental understanding of the material's properties as the particle size reaches the atomic scale has also been motivated. Due to their various applications in the biomedical field, magnetic nanoparticles (MNPs) have received special attention, such as magnetic drug delivery, cancer hyperthermia, contrast enhancers for magnetic resonance imaging (MRI contrast agent), DNA hybridization and cell separation. Recent studies have demonstrated that mixed-ferrites (MFe_2O_4 where M= Co, Zn) are promising candidates for biomedical and biotechnology applications due to their biocompatibility, good physical and chemical stabilities, ease of synthesis and suitable magnetic characteristics. Thus, a systematic study of Nano sized ferrite materials has become a fascinating subject of recent interest.

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