

Structural, Electrical and Magnetic Properties of Mixed Ferrite Nanoparticles

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Abstract - The potential applications of nano ferrites, particularly spinel ferrites, have sparked increased attention in the field of technology. It is possible for the characteristics of nanoferrite to be altered if "divalent, trivalent, or tetravalent impurities" are incorporated into the spinel lattice. Studying basic material characteristics may lead to new theories and concepts. Doping nano ferrites helps improve their performance and expand their applications. Nano ferrite samples were examined by "X-ray diffraction, FTIR spectroscopy, scanning electron microscopy, transmission electron microscopy, atomic force microscopy, energy dispersive x-ray spectroscopy, and wavelength dispersive x-ray fluorescence spectroscopy". Rare earth-doped nickel ferrite showed normal dielectric behaviour and reduced dielectric loss. Doped ferrites are suited for high-frequency applications due to increased resistivity and lower dielectric loss.

Keywords - Effects, Structural, Electrical, Magnetic Properties, Zinc–Magnesium, Mixed Ferrite Nanoparticles.

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INTRODUCTION

Currently, nanoscale research's most significant contributions are coming from the rapidly developing field of material science and technology. Due of its potential uses in fields such as electronics, optics, catalysis, ceramics, information storage, medicine and health care, etc., a new branch of material research called "nanomaterials and nanostructures" is gaining a lot of interest. Materials with innovative or improved characteristics are the driving force. Innovative nanosystems and nanostructured materials can be created as a result of the discovery of new materials, processes, and phenomena at the nanoscale and the development of new experimental and theoretical study tools. [1]

It is vital to understand the structural, electrical, electronic, chemical, and magnetic characteristics of nanomaterials in order to build the next generation of nano-devices. A worldwide effort is underway to develop nanomaterials with more complex and efficient tasks, such as materials that decompose pollutants more quickly [2], selective and highly sensitive sensors that can be used for medical diagnostics and treatment of cancer, efficient carriers for targeted drug delivery and hyperthermia treatment, tougher and harder cutting tools, high-density information storage or more efficiencies. Innovative nanomaterials with desired functional qualities are so likely to lead to new product generations that enhance both our well-being and our natural environment. [3]

Nanomaterials

It is possible to categorize nanomaterials as nonmaterial's everything having a characteristic length scale between one nanometer (nm) and a hundred nanometers (nm). There are no limits to how many atoms nanostructured materials can hold together. The characteristics of these particles are generally somewhere in between those of quantum and bulk materials. Life on Earth may have been able to form nanostructured materials since the beginning of time. Microorganisms, fine-grained minerals in rocks, nanoparticles in bacteria, and smoke are all instances of this phenomenon [4]. Nature produces a wide variety of nanomaterials. Because of the magnetic created by these tiny magnetite (Fe₃O₄) particles, Magnetosperillum Magnetotacticum bacterium is able to identify a growth direction that is most conducive to its development.

Synthesis perspective

Top-down and bottom-up methods are used to synthesise and fabricate nanomaterials and nanostructures, respectively. The top-down approach begins with a large piece of material and gradually reduces it to nanoscale, whereas the bottom-up method begins with a single atom and gradually increases in size until it reaches a nanostructure. In contrast to milling, colloidal dispersion is a good example of a bottom-up

process. To produce nanomaterials, nanotechnology relies heavily on both processes. [5]

Microscale items may be efficiently and reliably delivered via a top-down strategy. It's a tactic that gets more difficult as target structures get smaller and smaller. One of the drawbacks of the top-down technique is that the structure of the surface is not perfectly smooth. Traditional top-down processes like lithography, for example, are widely known to degrade processed patterns' crystallographic integrity, and etching can introduce further flaws [6]. Due to the increased surface-to-volume ratio, these flaws might have a major influence on the physical characteristics and surface chemistry of nanomaterials. At its most basic, a bottom-up strategy is one that starts from the ground up: atoms and molecules one by one; molecular chains one by one; and clusters one by one. Nanomaterials and nanostructures can't be created without using this technology, which isn't new [7]. There are fewer flaws, a more uniform chemical composition, and better short and long-range ordering in nanomaterials produced using bottom-up processes.

Properties

The structural properties of nonmaterial's fall between between those of atoms and bulk materials, making them unique. Materials with nanometer-sized dimensions have distinct characteristics that are distinct from those of atoms and bulk substances. Because of their nanometer dimension, these materials have a higher surface energy, more surface atoms, better spatial confinement, and fewer defects than their bulk counterparts. With their compact size and high surface area to volume ratio, nonmaterial's exhibit more surface-dependent characteristics due to their big surface area to volume ratio. However, it's possible that there are many more properties that have yet to be uncovered.

Nan materials' spatial confinement effects, which result in quantum phenomena, are a result of their nanometer feature sizes [8]. The characteristics of nonmaterials are profoundly affected by quantum confinement. Unlike bulk materials, nanoparticles have a very distinct energy band structure and charge carrier density, which affects their electrical and optical characteristics. The characteristics of nanoparticles are also influenced by the reduction of defects. These architectures and materials favor self purification processes in which the contaminates and inherent material faults will rise to the surface during annealing, making them easier to purify in the long run. [9]

The properties of nano-materials are described below:

- Melting Point
- Mechanical Properties
- Optical Properties
- Electrical and thermal conductivity

Magnetic nanomaterials

Magnetic nanoparticles and nanostructures have a unique place among the many well-known nanomaterials, thanks to their numerous technical and biological uses. Because of the groundbreaking work of Louis Neel and other early researchers, magnetic nanoparticles have garnered an increasing amount of attention over the past half-century. The magnetic characteristics of nanoparticles are strikingly different from those of the large materials from which they formed [10]. Due to finite size effects of the magnetic core and surface and interface effects associated with a lack of coordination for the particle's surface ions, they can cause exchange bonds to break, leading to frustration and spin disorder. The reduced number of co-operatively linked spins in the particle is one cause. Due of the greater surface-to-volume ratio, surface and contact effects become more prominent as particle size decreases. The 'giant spin' paradigm, which implies that all the spins participate in a single domain and that the magnetic energy is simply dictated by the particle volume and form, raises fundamental and demanding challenges for their theoretical explanation. All uses of magnetic nanoparticles rely heavily on surface and interface features [11].

Magnetism of nanoparticles

They have unusual properties, including as superparamagnetism and quantum tunneling of magnetization as well as improved magnetic coercivity. Magnetic saturation, coercive force, and Curie temperature are inherent characteristics of bulk materials that are solely dependent on chemical and crystallographic structure. The bulk sample's form and size are not critical. When compared to their bulk counterparts, magnetic nanoparticles exhibit a wide range of peculiar magnetic characteristics [12]. So-called finite-size and surface effects have a significant impact on the magnetic properties of nanoparticles.

Anisotropy in nanomaterials

There are two types of anisotropies in nanomaterials: crystalline anisotropy and shape anisotropy. Often, anisotropy is characterised as uniaxial and shown as a spherical shape (in its simplest form)

$$E = KV \sin^2 \theta$$

Where θ is the angle between the moment and the easy axis, and V is the volume of the particle, K is the effective uniaxial anisotropy energy per unit volume.

Using spin-orbit coupling, magnetocrystalline anisotropy may be generated, which favors alignment of the magnetization in a certain crystallographic direction. The "easy axis" of a material refers to the direction that the magneto crystalline anisotropy favors. Regardless of particle form, a particular material has a magnetocrystalline

anisotropy that is unique to that material [13]. Increasing the anisotropy of a material increases its coercivity, which makes it a good option for high-coercivity applications.

Superparamagnetism

Consider an assembly of identical single domain particles with uniaxial anisotropy. The energy per particle is,

$$U = -K_1 V \sin^2 \theta$$

is the angle between the easy axis and the single particle magnetic moment. $E_b = K_1 V$ is the energy barrier that a magnetic nanoparticle must overcome in order to rotate its magnetization. The anisotropy barrier can be bypassed by thermal fluctuations, as initially suggested by Neel, allowing a magnetic nanoparticle to spontaneously reverse its magnetization from one easy direction to the other. Despite its paramagnetic properties, the nanoparticles' magnetic moment fluctuates [14], rather than the atomic moment of a bulk paramagnetic substance. Superparamagnetism is the name given to this type of magnetic behavior in nanoparticles.

Ferrites

There are several uses for polycrystalline ferrites in a wide range of industries from catalysis to information storage to electronics to medical diagnostics to drug administration, and they are the most extensively utilized oxide magnetic nanomaterial. For many millennia, ancient societies have been aware of the existence of ferrite materials. Lodestone (Fe_3O_4) was used in Chinese compasses as far back as the 12th century [15]. In contrast, contemporary ferrites were not researched for their magnetic structure or electrical characteristics until the 1930s. In 1909, Hilpert published the first comprehensive analysis of the chemical composition and magnetic characteristics of several ferrites. Forestier presented a chemical investigation on the synthesis of several ferrites and the measurements of their saturation magnetization and Curie temperature about twenty years after Hilpert's discovery. Ferrites could not be improved to commercial levels by him, despite his best efforts [16]. Permeability of mixed ferrites was increased by many tens of times by Kato and Takei in 1932, which led to the first commercial ferrite cores.

Crystal structure of spinel ferrite

Named after the mineral spinel ($MgAl_2O_4$), which was discovered by Bragg in 1915, the spinel structure is named after the material itself. Fe_2O_4 MFe_2O_4 MFe_2O_4 is the general formula for magnetic spinel ferrites where M is a divalent metal ion such as Mn^{2+} , Ni^{2+} , Cu^{2+} , Co^{2+} , Fe^{2+} , Zn^{2+} , Mg^{2+} , Cd^{2+} or more often a combination of these. Spinel's magnetic moment can be enhanced by the presence of Fe^{2+} , Ni^{2+} , Co^{2+} , and Mn^{2+} , all of which have unpaired

electron spins. There are other divalent ions that do not contain unpaired electrons but instead enhance the magnetic moment by displacing the Fe^{3+} ions on the crystal lattice sites.

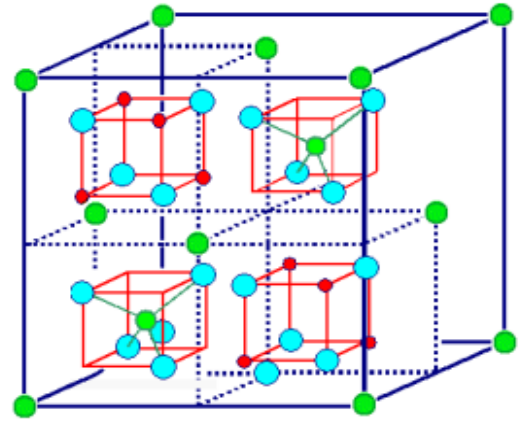


Figure 1: Crystal structure of spinel ferrite

Exchange Forces

In order to comprehend ferrites' ferrimagnetism, one must first understand the interactions that lead to spin ordering. P. Weiss proposed his molecular field idea in 1906 to explain magnetic ordering in ferromagnetic materials. However, it wasn't until 1928 that Heisenberg demonstrated that the molecular field, which tries to align neighboring spins, was driven by quantum mechanical exchange forces.

Neel's Theory of Ferrimagnetism

It's impossible for ferromagnetic materials like ferrites to have direct exchange interactions with positive metal ions that carry the magnetic moment because the extent of overlapping the wave functions diminishes exponentially with distance. As a result, in ferrites, an indirect exchange process known as super exchange mediates the exchange contact between metal ions. Antiparallel alignment is the lowest in energy due to the negative JEX (exchange energy) between the spins of the nearby metal ions. [17]

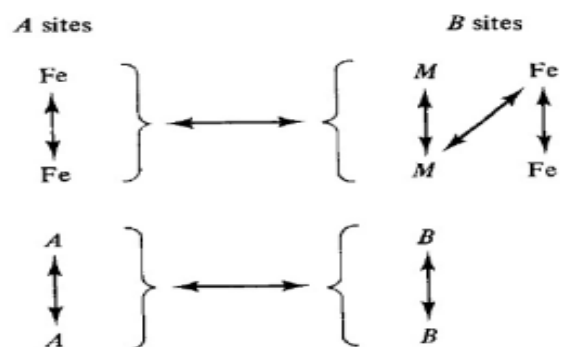


Figure 2: Exchange interactions between ions in an inverse cubic ferrite

Ferromagnetic materials have A and B sites that differ crystallographically because an ion's number and arrangement of neighbors differs between A and B sites. The exchange interactions that would have to be taken into account in a thorough treatment of $\text{MO.Fe}_2\text{O}_3$. In total, there are five interactions depicted by arrows [18].

Electrical Properties of ferrites

General electrical properties of ferrites including the temperature dependence of dc resistivity and the conduction mechanism are as follows:

1. Dc Resistivity

Verwey and subsequently Van Uitert and Jonker carried out extensive research into the origins of spinels' electrical conductivity. The resistivity of ferrite at normal temperature ranges from around 10^{-3} to 10^{11} cm depending on the chemical composition. According to Verwey's theory, ferrous and ferric ions occupy equivalent lattice locations (octahedral sites) in ferrites, which results in their low resistivity. Relatively speaking, magnetite, Fe_3O_4 , has a resistivity in the range of 10^{-2} to 10^{-3} cm, while in Ni-Zn ferrite, Koops observed that the resistivity rose around 103 times when the material included 0.42 percent ferrous oxide. Ferrites' resistivity changes with temperature according to the Arrhenius law.

$$\rho = \rho_0 \exp(\Delta E/kT)$$

Where ρ is the resistivity and ΔE is necessary for electron hopping across lattice sites to be activated. Ferrites' resistivity reduces as temperature rises, according to this relationship. At temperatures close to the Curie temperature, the logarithmic connection between \log and T^{-1} appears to be linear; nevertheless, these curves break at these temperatures. [19]

2. Conduction Mechanism

In spite of their negative temperature coefficient of resistance, ferrites do not have the same conduction mechanism as semiconductors do even if they display this property. There is a difference between semiconductors and ferrites when it comes to band-type conduction. In semiconductors, cations are surrounded by tightly packed oxygen anions and are considered to be isolated. Because the orbitals will have some direct overlap, a localized electron model is preferable to a collective electron model [20]. This explains ferrites' insulating properties. Since drift mobility of the charge carriers is influenced by temperature, it is difficult to determine how temperature changes effect carrier concentration.

CONCLUSION

Nanocrystalline spinel ferrites are technologically significant due to their wide range of uses, and it is expected that ferrite production will rise year after year as their applications grow more varied. Ferrites have advantages such as higher frequency application, lower price, very high electrical resistivity, stronger heat resistance, and superior corrosion resistance, despite their saturation magnetization being less than half that of ferromagnetic alloys. The replacement of terbium and gadolinium causes the unit cell to expand, whereas samarium doping causes the lattice constant of magnesium ferrite to decrease. In Mg-Zn ferrite, gadolinium and samarium doping restrict grain development, but terbium doping increases it.

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