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Structural, Electrical and Magnetic Properties of Doped Zinc Ferrites: A Review

Ningurkar A. D, Bajpeyee A. U

Smt. Narsamma ACS College, Kiran Nagar, Amravati (MS), India 444606

ABSTRACT: Zinc ferrite ($ZnFe_2O_4$) is a technologically significant soft magnetic material belonging to the normal spinel family, widely employed in sensors, high-frequency magnetic cores, microwave devices, catalysts, and data-storage components. Owing to its versatile crystal chemistry, the structural, electrical, and magnetic characteristics of $ZnFe_2O_4$ can be deliberately tuned through controlled substitution of foreign cations (dopants). This tunability makes doped zinc ferrites an important class of functional materials for next-generation electronic and magnetic applications.
Extensive research has explored the influence of various dopants—including aluminium (Al^{3+}), cobalt (Co^{2+}), copper (Cu^{2+}), nickel (Ni^{2+}) and manganese (Mn^{2+}/Mn^{3+}) on the microstructure, cation distribution, electrical transport behaviour, and magnetic response of $ZnFe_2O_4$. The synthesis route and dopant concentration critically determine crystallite size, lattice distortion, oxygen stoichiometry, and the redistribution of cations between tetrahedral (A) and octahedral (B) sites. These cationic rearrangements, in turn, govern key properties such as hopping-based electrical conductivity, superexchange interactions, saturation magnetisation, and coercivity.
This review consolidates current developments in doped $ZnFe_2O_4$ systems, highlighting the correlations between synthesis parameters, structural modification, and functional performance. Special emphasis is placed on nanoscale systems, multi-dopant strategies, and environmentally benign synthesis approaches that aim to enhance application-specific behaviour. Remaining challenges and future directions are outlined to support further optimisation of zinc ferrite-based materials for advanced electronic, magnetic, and energy-related technologies.

KEY WORDS: Cation distribution; Electrical conductivity; Zinc ferrite; Dopant effects; Spinel structure; Magnetic properties; Nanostructured ferrites.

I. INTRODUCTION

Zinc ferrite ($ZnFe_2O_4$) is a spinel-type material with a normal spinel structure. In this structure, Zn^{2+} ions are found in the tetrahedral sites, while Fe^{3+} ions occupy the octahedral sites. It has a cubic crystal form belonging to the Fd-3m space group, which is common for spinel ferrites. $ZnFe_2O_4$ shows useful electrical and magnetic properties, making it suitable for many applications. Adding (doping) different elements into $ZnFe_2O_4$ can further improve its performance in sensors, electronic devices, catalytic processes, and biomedical uses[1].$ZnFe_2O_4$ has a normal spinel structure in which Zn^{2+} ions occupy the tetrahedral sites and Fe^{3+} ions sit in the octahedral sites. It has a cubic crystal structure with the space group Fd-3m. When doped with other elements, this structure can change into a mixed spinel form[2].
$ZnFe_2O_4$ shows superparamagnetic behavior and has good saturation magnetization at room temperature. It also has high electrical resistance and low eddy current losses, which makes it useful for magnetic and dielectric applications. Although its saturation magnetization is lower than many other ferrites, it can be improved by adding suitable dopants[3,4].
Doping $ZnFe_2O_4$ with elements such as Co, Ni, Cu, Mn, Al, or rare-earth ions can improve both its magnetic and electrical properties. These dopants can change the normal spinel structure into a mixed spinel form, which increases magnetization and can modify the Curie temperature. Because of these improvements, doped $ZnFe_2O_4$ is widely used in sensors, electronic devices, catalytic applications, and biomedical fields[4].
Elements such as Co, Ni, Cu, Mn, Al, and rare-earth ions are commonly added to $ZnFe_2O_4$ to improve its properties. These dopants change the cation distribution and magnetic interactions, leading to better electrical and magnetic performance. Although $ZnFe_2O_4$ normally has a normal spinel structure, doping can convert it into a mixed or inverse spinel form, which strongly influences its behavior. By selecting the right dopant and synthesis method, the properties of $ZnFe_2O_4$ can be tuned for specific applications, showing its high versatility and technological potential[5].

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II. SYNTHESIS & MICROSTRUCTURE OF ZINC FERRITE

The synthesis of nanoferrites can be done using several methods, such as solid-state, sol-gel, co-precipitation, and hydrothermal techniques. Each method affects the particle size, cation distribution, and overall properties of the ferrite material. Choosing the right synthesis method is especially important for doped nanoferrites because it controls how well the dopants are mixed and distributed. This directly influences the magnetic and structural behavior of the final product.

A. Synthesis

- **Solid-State Method**:
  A traditional high-temperature method where solid reactants are mixed and heated. It is simple and low-cost but usually produces larger particles and requires more energy. This method changes a colloidal solution into a gel, which is then heated to form zinc ferrite. It helps maintain the correct chemical ratio and produces a clean, well-structured polycrystalline material with very few defects [6].
- **Sol–Gel Method**:
  This method provides good control over particle size and uniformity. A solution is converted into a gel and then heated. It is effective for making small, uniform particles and is widely used for doped ferrites[7].
- **Co-precipitation**:
  In this method, different ions are precipitated together from a solution. It produces fine particles with good control over composition, but sometimes needs additional treatments to improve the final properties.In this method, zinc ferrite is made by forming mixed hydroxides from nitrate solutions, and then heating them. This process can produce nanoparticles between 12 and 48 nm in size, depending on the temperature used during calcination.[8].
- **Hydrothermal Method**:
  This technique uses high temperature and pressure inside a sealed vessel. It produces well-crystallized particles with controlled shape and good quality[9].
- **Microwave-Assisted Synthesis:**
  This method greatly shortens the reaction time and produces evenly distributed, very fine particles. It is effective for making zinc ferrite with a single-phase, face-centered cubic structure[10].

  The co-precipitation method has many advantages for making zinc ferrites, so it is widely used. This method is useful because it can produce materials that are very pure, uniform, and have a well-controlled structure. These qualities help improve the magnetic and physical properties of zinc ferrites. It also allows the formation of very small (nanosized) particles, which are important for better performance in different technologies. The main benefits of the co-precipitation method for zinc ferrites are given below.

- **High Purity and Uniformity:**
  The co-precipitation method helps make zinc ferrites that are very pure and uniform. This is important because it gives consistent material properties. This happens because the chemical composition is controlled at the molecular level during the process[13,14].
- **Controlled Microstructure:**
  This method gives very good control over the microstructure of zinc ferrites, leading to a single-phase cubic spinel structure. This control is important for improving the magnetic and dielectric properties of the material[15,14].
- **Nanosized Particles:**
  The co-precipitation method is good for making very small (nanosized) particles. These tiny particles are useful in applications that need high surface area and improved magnetic properties. The particle size can be adjusted by changing factors like temperature and chemical concentration during synthesis[15,16].
- **Improved Magnetic Properties:**
  Zinc ferrites made using the co-precipitation method show better magnetic properties, such as higher magnetization and more controlled permeability, than those made by older methods. Because of this, they are useful for high-frequency devices and magnetic shielding[17.18].
- **Lower Temperature Needed :**
  The co-precipitation method works at lower temperatures than traditional ceramic methods. This reduces energy use and helps produce materials with finer microstructures[13].Although the co-precipitation method has many advantages, it is sensitive to factors like pH, temperature, and the concentration of chemicals used. These

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conditions must be controlled carefully to get the desired material properties. Also, even though this method works well for making high-quality zinc ferrites, it may not be suitable for all ferrite types. In some cases, other synthesis methods may be needed depending on the application.

III. STRUCTURAL, ELECTRICAL & MAGNETIC PROPERTIES FOR ZINC FERRITES

Zinc ferrites, especially $ZnFe_2O_4$, have important structural, electrical, and magnetic properties. These properties depend on factors like the synthesis method, the amount of dopant added, and the sintering conditions. They are very important for use in electronics, magnetic devices, and catalysis. Zinc ferrites usually have a cubic spinel structure, and their electrical and magnetic behavior can be adjusted by changing their composition and processing steps.

A. Structural Properties

Zinc ferrites normally have a cubic spinel structure, which is confirmed by X-ray diffraction (XRD) in many studies. The crystallite size can vary widely depending on the synthesis method and the amount of dopant added, usually ranging from 22 nm to 80 nm. The lattice parameter and density also change with the type and concentration of dopant. For example, dopants with a larger ionic radius, such as Cd, can increase the lattice parameter.

The effect of dopants on the structural properties of zinc ferrites is complex. Dopants can change the crystallite size, phase purity, structural stability, microstructure, and lattice strain. Many studies show that adding different dopants significantly influences the overall behavior and properties of zinc ferrites.

- **Crystallite Size Variation:**
  Bismuth doping in zinc ferrite produces crystallite sizes of about 16–20 nm and increases the lattice parameter because Bi^{3+} ions are larger than Fe^{3+} ions[19]. Chromium doping increases the crystallite size from 22 nm to 36 nm in zinc ferrite, while magnesium doping in nickel ferrite slightly reduces the crystallite size from 24.8 nm to 22.5 nm[20]. Gadolinium doping in nickel ferrite decreases the crystallite size from 25 nm to 11 nm, showing that rare earth elements can strongly affect crystallite size[19,20].
- **Phase Purity and Structural Stability:**
  All doped samples across various studies maintain a single-phase cubic spinel structure, indicating high phase purity and structural stability despite the introduction of dopants. The stability of the spinel phase is confirmed through XRD analysis, which shows no secondary phases or impurities[21].
- **Microstructural Changes:**
  SEM and TEM studies show that dopants can cause agglomeration and uneven grain growth, such as in magnesium- and manganese-doped ferrites. In most cases, doped ferrites have a spherical and fairly uniform particle shape, but some dopants, like manganese, can create porous and non-uniform structures[22]

- **Lattice Strain & Defect Formation:**
  Lattice strain usually increases as the dopant concentration rises, as seen in gadolinium-doped nickel ferrite, where higher strain is linked to a decrease in lattice parameters. Adding dopants can also create defects in the structure, which appear as changes in lattice strain and dislocation density. These defects can affect the overall strength and stability of the material. Although dopants can improve certain properties of spinel ferrites, they may also introduce challenges like higher lattice strain and more defects. Therefore, choosing the right dopant and its proper concentration is important to achieve the desired structural properties[23].

B. Electrical Properties

The electrical properties of zinc ferrites change a lot when different metal ions (dopants) are added. Doping mainly affects how electrons move, the energy needed for conduction, dielectric behavior, impedance, and both AC and DC conductivity[24].When dopants are introduced, they change the electron hopping between Fe^{2+} and Fe^{3+} ions, which directly modifies the electricalconductivity[25]. The activation energy, which shows how much energy is needed for electrons to move, also varies with different dopants. This gives useful information about the conduction mechanism.

- **Dielectric properties:**
  The dielectric properties—such as dielectric constant and dielectric loss—depend on the type of dopant, the frequency of the applied field, and the microstructure of the ferrite. Impedance behavior, which includes contributions from both grains and grain boundaries, also changes with dopant concentration and synthesis method[26].

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- **Conductivity:**
  Conductivity shows different trends with frequency. In general, the AC conductivity of zinc ferrites increases as frequency increases, which is typical for dielectric materials. The dielectric was observed at specific zinc concentrations. Factors such as grain size and porosity further influence AC conductivity and dielectric behavior; materials with smaller grains often show higher permittivity and higher conductivity[27].
- **Electrical Conductivity and Electron Hopping:**
  Doping changes the electron hopping between Fe^{2+} and Fe^{3+} ions, which directly affects the conductivity of zinc ferrites. For example, when yttrium is added to cobalt zinc ferrites, the electrical behavior depends on both grain size and frequency. This shows the presence of Maxwell–Wagner type interfacial polarization. Similarly, aluminium (Al) doping in zinc ferrites also changes their electrical properties. It reduces the energy band gap and causes noticeable variations in the dielectric constant and dielectric loss[28].
- **Activation Energy:**
  Activation energy changes when different amounts of dopants are added, and this directly affects how conduction takes place in the material. In Cu–Zn ferrites, the activation energy increases as the zinc content increases, which in turn influences the DC resistivity[29].
- **Dielectric Properties:**
  The dielectric constant and dielectric loss change depending on the type of dopant and the applied frequency. In aluminium-doped zinc ferrites, both the dielectric constant and loss decrease and then become stable at higher frequencies. Likewise, when zinc is substituted in lithium ferrites, the dielectric constant decreases as the frequency increases[30].
- **Impedance Characteristics:**
  Grain and grain-boundary contributions shift with dopant concentration. In Ni-Zn ferrites, the microstructure and grain size are influenced by Zn content, affecting impedance[31].
- **AC and DC Conductivity:**
  Doped zinc ferrites show different conductivity patterns with changing frequency. For example, in Cu–Zn ferrites, AC conductivity increases with frequency, which agrees with the electron-hopping conduction model. In Co–Zn ferrites, AC conductivity is improved due to charge-transfer processes[32].

Although doping usually enhances the electrical performance of zinc ferrites, the choice of dopant must match the needs of the intended application. Some dopants may increase conductivity or improve dielectric behavior, but they can also create challenges related to synthesis, microstructural stability, or long-term performance. Therefore, understanding the balance between improved properties and potential limitations is essential for optimizing zinc ferrites for specific technological uses.

C. Magnetic Properties

Zinc ferrites show ferromagnetic behavior, and their saturation magnetization and coercivity depend strongly on how much zinc or other dopants are added[33,34].When non-magnetic ions like Zn^{2+} replace magnetic ions, the magnetization decreases because the magnetic interactions become weaker.Magnetic properties can also be adjusted by changing how cations are distributed between tetrahedral and octahedral sites, as seen in studies using Mg and Cr substitutions[35].
Overall, the magnetic and electrical properties of zinc ferrites are strongly affected by the synthesis method and the type of dopants used. Different synthesis methods, such as sol–gel and combustion, can change the particle size and shape, which then changes the material's final properties. This shows how important it is to carefully control the synthesis process to get zinc ferrites with the right properties for specific applications.

- **Saturation Magnetization (Ms):**
  Saturation magnetization in zinc ferrites depends strongly on both particle size and chemical composition. For example, $ZnFe_2O_4$ nanocrystals can show a saturation magnetization of 65.4 emu/g at 10 K, mainly because of the degree of inversion in the spinel structure. In non-stoichiometric zinc ferrite nanoparticles, annealing can greatly increase the saturation magnetization due to cation rearrangement and the partial reduction of Fe^{3+} to Fe^{2+}. In Ni–Zn ferrites, the saturation magnetization decreases as the zinc content increases, clearly showing how composition affects the magnetic behavior[36].
- **Coercivity (Hc):**
  Coercivity in zinc ferrites is usually low, which is typical for soft magnetic materials. For example, $Ni_{0.6}Zn_{0.4}Fe_2O_4$ ferrites have a coercivity of about 1.2 Oe, making them suitable for applications that require very low coercive fields. In contrast, $ZnFe_2O_4$ nanocrystals show a coercivity of around 102 Oe in the blocked state, indicating the presence of small particle anisotropy[37].

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- **Curie Temperature (Tc):**
  The Curie temperature of zinc ferrites changes with variations in composition. For example, in Ni–Zn ferrites, increasing the zinc content lowers the Curie temperature (Tc), and at the highest zinc levels, Tc can even drop below room temperature. In contrast, when tin (Sn) is substituted into Ni–Zn ferrites, the Curie temperature increases, showing how substitution can enhance the thermal stability of the material[38].
- **Superparamagnetic/Nanoscale Effects:**
  Zinc ferrite nanoparticles often show superparamagnetic behavior at room temperature. For example, $ZnFe_2O_4$ nanocrystals have a blocking temperature of about 68 K. Superparamagnetism is also observed in Mg–Zn ferrites, where temperature-dependent AC susceptibility confirms this behavior. Although the magnetic properties of zinc ferrites are well studied, different synthesis methods and heat treatments can still cause noticeable variations. For instance, the sintering temperature strongly affects the magnetic parameters of Ni–Zn ferrites. These differences highlight how processing conditions influence magnetic behavior and show that zinc ferrite is a highly tunable material suitable for a wide range of technological applications[39].

D. Microstructural Characteristics

- **Crystallite Size and Structure:**
  Zinc ferrite usually has a spinel structure, and its crystallite size depends on how it is made. Methods like sol-gel and co-precipitation can produce crystallite sizes ranging from about 3–4 nm up to 48 nm[40].
- **Morphology:**
  The microstructure of zinc ferrite can vary from spherical to rod-shaped, depending on the synthesis conditions. Some methods, like sol-gel autocombustion, can even produce a sponge-like structure with large pores[41].
- **Lattice Parameters:**
  Variations in lattice parameters are observed with changes in particle size and synthesis conditions, affecting the material's magnetic properties[42]. Although zinc ferrite's synthesis and microstructure are well understood, it is still challenging to fine-tune these factors for specific applications. The selected synthesis method and conditions can greatly influence important properties like magnetic permeability and electrical resistivity.

E. Applications of Zinc Ferrites

Zinc ferrites, especially $ZnFe_2O_4$, are useful materials with many applications because of their special magnetic, electrical, and structural properties. They are used in electronics, optoelectronics, and catalysis due to their high electrical resistance and strong magnetic behavior. However, using zinc ferrites also comes with challenges, mainly in controlling their structure and magnetic properties for specific needs. The sections below explain the applications and challenges of zinc ferrites.

- **Electronics and Optoelectronics**:
  Zinc ferrites are used in electronic devices because they have high electrical resistivity and good magnetic properties. They are especially important in high-frequency devices like inductors and transformers, where they help reduce energy losses[26].Zinc ferrites are used in parts like inductors and transformers because they have high electrical resistance and work well at high frequencies[43]
- **Catalysis:**
  Their high surface area and chemical activity make zinc ferrites useful in catalytic processes. They are also used in high-density information storage and ferrofluids[44].
- **Biomedical Applications:**
  Zinc ferrites may be used in drug delivery and as contrast agents in MRI, thanks to their superparamagnetic behavior[28].Zinc ferrites can be used in the medical field, especially for delivering medicines and treating cancer. Because they have magnetic properties, they can carry drugs to a specific part of the body and can also produce controlled heat to help kill cancer cells (hyperthermia treatment)[42,43].
- **Magnetic Devices:**
  They are used in devices such as pulsed magnets and accelerators because they offer fast magnetization and low switching losses[44].Zinc ferrites are important in making pulsed magnetic devices used in accelerators and laser systems. They can handle very fast magnetic changes, which makes them useful for devices that need quick magnetic responses.Ni-Zn ferrites are used in pulsed magnetic devices like high-speed kicker magnets in particle accelerators. They can handle very fast changes in magnetization, which makes them suitable for systems that need quick magnetic field switching, such as pulse-power equipment and laser devices[41,43].

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F. Challenges in Zinc Ferrites

- **Synthesis and Doping:**
  Making zinc ferrites—especially nanomaterials—requires careful control of particle size and distribution. Adding dopants like aluminum can change their structure and magnetic properties, but achieving the perfect combination can be difficult[41,45].
- **Sintering Conditions:**
  The magnetic and structural properties of zinc ferrites change a lot with sintering temperature and time. These conditions must be optimized for good performance[45].
- **Dielectric Properties:**
  For high-frequency applications, the dielectric constant and loss must remain stable at different frequencies. This requires precise control over composition and processing steps.
  Even though zinc ferrites have many useful applications, challenges in their synthesis and optimization show that more research is needed. Future advances in materials science could improve their properties and make them even more valuable for new technologies.

IV. CONCLUSION

Zinc ferrites, especially $ZnFe_2O_4$, show useful structural, electrical, as well as magnetic properties that make them valuable for catalysis, electronics, magnetic devices, and biomedical applications. Their performance strongly depends on factors such as synthesis method, dopant type, particle size, and sintering conditions. Methods like co-precipitation can produce nanosized, high-purity materials, while dopants help tune lattice parameters, magnetization, and dielectric behavior. However, achieving the desired properties requires strict control over pH, concentration, temperature, and processing steps. Although zinc ferrites offer many advantages, challenges remain in optimizing their magnetic behavior, microstructure and dielectric stability for specific applications. Continued research on synthesis control and dopant engineering will help further improve the functional performance of zinc ferrites and expand their use in advanced future technologies.

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