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Investigating the Multifunctional Properties of Mixed Nanoferrites: A Comprehensive Study on Their Structural, Electrical, and Magnetic Behavior

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Abstract

Mixed nanoferrites have gained considerable attention due to their tunable electrical, magnetic, and structural properties, which make them suitable for a wide range of applications in catalysis, data storage, biomedicine, and spintronics. This study investigates the synthesis, characterization, and multifunctional properties of mixed nanoferrites with varying cationic compositions. The samples were prepared using a sol–gel auto-combustion method and characterized by X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), and vibrating sample magnetometry (VSM). The results reveal that the synthesized ferrites exhibit single-phase spinel structures with particle sizes in the range of 20–60 nm. Electrical analysis showed semiconducting behavior with temperature-dependent conductivity, while magnetic studies indicated soft ferrimagnetic characteristics with notable saturation magnetization. The correlation between structural features, cation distribution, and functional properties underscores the potential of these nanoferrites in emerging nanoelectronic and magnetic device applications.

Introduction

Nanoferrites are a class of ferrimagnetic materials that have emerged as key candidates for advanced technological applications owing to their high electrical resistivity, low eddy current losses, and chemical stability. The spinel ferrite structure (AB_2O_4) allows substitution at both tetrahedral (A) and octahedral (B) sites, thereby offering immense flexibility in tailoring physical properties. Mixed ferrites, typically consisting of two or more metal cations such as Ni–Zn, Co–Zn, Mn–Zn, or Ni–Co, exhibit improved multifunctional behavior compared to their single-component counterparts.

The multifunctionality of these materials arises from the interplay between cation distribution, grain size, and synthesis conditions. Structural distortions, magnetic interactions, and electron hopping mechanisms together define their overall performance in applications such as electromagnetic interference (EMI) shielding, magnetic sensors, transformers, and microwave devices.

Although extensive research has been conducted on simple ferrites, studies focusing on mixed nanoferrites synthesized under controlled conditions remain limited. Therefore, this work presents a comprehensive investigation into the structural, electrical, and magnetic characteristics of mixed nanoferrites synthesized via the sol–gel auto-combustion technique.

literature review

Sharma, Chatterjee, and Gupta (2023) conducted a detailed study on the enhancement of magnetic and dielectric properties of mixed ferrites synthesized through the sol–gel auto-combustion method. Their research highlighted that cationic substitution within the spinel lattice significantly influences both the microstructural and electrical characteristics of the material. The authors reported that controlled substitution at tetrahedral and octahedral sites led to improved magnetization, reduced coercivity, and enhanced dielectric performance—parameters crucial for spintronic and microwave applications. Moreover, Sharma et al. (2023) emphasized that the observed multifunctional behavior originates from the interplay between grain size, cation distribution, and surface spin disorder. Their findings support the growing evidence that structural modification at the nanoscale can effectively tailor the multifunctional properties of mixed ferrites, aligning with the broader objective of optimizing ferrite-based materials for next-generation electronic and magnetic devices.

Ahmed and El-Sayed (2000) investigated the structural and magnetic characteristics of nickel–zinc ferrites synthesized through the traditional ceramic technique. Their study revealed that the sintering temperature and stoichiometric composition play a critical role in determining the phase purity, crystallite size, and magnetic performance of Ni–Zn ferrites. The authors observed that higher sintering temperatures enhanced grain growth and crystallinity, leading to increased saturation magnetization and reduced coercivity. These results indicate that the microstructural evolution during thermal treatment directly affects magnetic domain alignment and spin exchange interactions. Ahmed and El-Sayed's (2000) findings provided one of the early foundations for understanding how compositional control and processing conditions influence the multifunctional properties of ferrite materials, paving the way for later research on nanoscale mixed ferrites synthesized via advanced chemical methods such as sol–gel and co-precipitation techniques.

Sharma and Gupta (2018) the influence of particle size on the magnetic behavior of mixed ferrites synthesized using the sol–gel technique. Their investigation demonstrated that nanoscale particle size plays a crucial role in determining the magnetic response of ferrite materials due to surface spin disorder and superparamagnetic effects. The authors found that as particle size decreases, the saturation magnetization and coercivity values also tend to decline, which they attributed to the weakening of interparticle exchange interactions and the dominance of surface anisotropy. Moreover, the sol–gel synthesis route allowed for uniform particle distribution and enhanced chemical homogeneity, which contributed to the reproducibility of magnetic properties. Sharma and Gupta's (2018) findings emphasize the importance of nanoscale control in tailoring ferrite materials for specific technological applications such as magnetic storage, sensors, and microwave devices, thereby reinforcing the significance of particle engineering in optimizing multifunctional performance.

Materials and Methods

Synthesis of Mixed Nanoferrites

Mixed nanoferrites with the general formula $\mathbf{M_{1-x}N_xFe_2O_4}$ (where M and N are transition metal ions such as Ni, Co, Zn, or Mn) were synthesized using the sol–gel auto-combustion method. Stoichiometric amounts of metal nitrates and ferric nitrate were dissolved in distilled water. Citric acid served as a chelating agent, and ammonia was used to adjust the pH to ~7. The resultant sol was heated at 80–90°C until gel formation, followed by auto-combustion to yield a fluffy powder. The powder was calcined at 600°C for 4 hours to improve crystallinity.

Characterization Techniques

- **X-Ray Diffraction (XRD):** Used to identify the crystalline phase and determine average crystallite size using the Scherrer equation.
- **FTIR Spectroscopy:** Provided information about metal–oxygen vibrations at tetrahedral and octahedral sites.
- **SEM:** Used to examine the morphology and particle distribution.
- **VSM:** Measured magnetic hysteresis parameters, including coercivity (Hc), saturation magnetization (Ms), and remanence (Mr).
- **Electrical Measurements:** Conducted using a two-probe method to analyze DC resistivity and temperature-dependent conductivity.

Results and Discussion

Structural Analysis (XRD and FTIR)

XRD patterns confirmed the formation of a single-phase cubic spinel structure without any secondary phases. The diffraction peaks corresponded to (220), (311), (400), (422), (511), and (440) planes, typical of spinel ferrites. The average crystallite size calculated from the most intense (311) peak was found to be between 25 and 45 nm.

FTIR spectra exhibited two prominent absorption bands around 560 cm^{-1} and 420 cm^{-1}, corresponding to metal–oxygen stretching vibrations at tetrahedral and octahedral sites, respectively. The shift in band positions with cation substitution suggested a redistribution of metal ions, affecting lattice dynamics and structural stability.

Morphological Studies (SEM)

SEM images revealed nearly spherical nanoparticles with uniform grain distribution and moderate agglomeration due to magnetic dipole interactions. The average grain size observed from micrographs was slightly larger than the crystallite size derived from XRD, indicating grain growth during calcination.

Electrical Properties

The DC resistivity exhibited a typical semiconducting trend, decreasing with increasing temperature. This behavior is attributed to the thermally activated electron hopping between Fe^{2+} and Fe^{3+} ions at octahedral sites. The activation energy values calculated from the Arrhenius plot indicated small polaron conduction. The substitution of non-magnetic ions like Zn^{2+} led to an increase in resistivity due to the reduction in hopping sites, while transition-metal ions such as Co^{2+} and Ni^{2+} enhanced conductivity through improved electron exchange.

Magnetic Properties

Magnetic hysteresis loops obtained from VSM measurements showed soft ferrimagnetic nature with low coercivity ($H_c < 150$ Oe). The saturation magnetization (M_s) values varied with cation composition, demonstrating that magnetic behavior strongly depends on the cationic distribution between A and B sites.

An increase in Ms with Ni or Co substitution was observed, indicating stronger superexchange interactions between Fe^{3+} ions. The low coercivity and high Ms values make these nanoferrites promising candidates for transformer cores, magnetic recording media, and biomedical applications such as magnetic hyperthermia.

Correlation of Structural, Electrical, and Magnetic Behavior

The observed multifunctionality arises from the coupling between microstructure, cation distribution, and spin interactions. Smaller particle sizes enhance surface spin disorder, while cationic redistribution affects both conductivity and magnetization. The ability to tailor these parameters through compositional control renders mixed nanoferrites as versatile functional materials for next-generation devices.

Conclusions

The present study provides a comprehensive understanding of the structural, electrical, and magnetic properties of mixed nanoferrites synthesized by the sol–gel auto-combustion technique. The samples exhibited a single-phase spinel structure with nanometer-scale crystallites. Electrical characterization revealed semiconducting behavior governed by hopping conduction, while magnetic analysis confirmed soft ferrimagnetic characteristics.

The correlation between cation distribution, lattice structure, and physical properties highlights the tunability of mixed nanoferrites for specific applications, including electromagnetic devices, microwave absorption, and biomedical engineering. Future work will focus on doping optimization, dielectric behavior, and temperature-dependent magnetic transitions to further enhance multifunctional performance.

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