

Influence of Ga^{3+} – Al^{3+} Co-substitution on the Structural and Morphological Characteristics of Spinel CoFe_2O_4 Nanoparticles

Vivek Chintaman Patil¹, Archana D. Chapolikar², Vishaljyot Divekar³, Vaibhav Devidas Murumkar⁴

¹Mangaon Taluka Education Society's Doshi Vakil Arts College and G.C.U.B. Science & Commerce College, At-Goregaon, Tal-Mangaon, Dist-Raigad- 402103, M. S. India

²Department of Chemistry, Government College of Arts and Science, Chatrapati Sambhajanagar, 431001

^{3,4}Department of Physics, Vivekanand college, Chhatrapati Sambhajanagar. 431001, M. S. India

*Corresponding Author: murumkarvd@gmail.com

Mobile No.: 9422686322

ABSTRACT

$\text{CoFe}_{2-2x}\text{Ga}_x\text{Al}_x\text{O}_4$ ($x = 0.1$ and 0.3) nanoparticles were synthesized by the sol–gel auto-combustion method and characterized to investigate their structural and morphological properties. X-ray diffraction (XRD) analysis confirmed the formation of a single-phase cubic spinel structure with no detectable impurity phases. The diffraction peaks corresponding to the (220), (311), (222), (400), (422), (511), and (440) planes indicated high crystallinity and successful incorporation of Ga^{3+} and Al^{3+} ions into the CoFe_2O_4 lattice. Transmission electron microscopy (TEM) revealed nearly spherical nanoparticles with slight agglomeration and particle sizes of 40–70 nm, demonstrating the suitability of the synthesized ferrite nanoparticles for multifunctional applications.

Keywords: Spinel Ferrite, Sol–gel auto-combustion, X-ray diffraction. Transmission electron microscopy; Nanoparticles.

1. Introduction

Nanomaterials have attracted significant attention owing to their unique physical and chemical properties that differ remarkably from their bulk counterparts[1]. Their high surface-to-volume ratio, tunable electronic structure, and enhanced magnetic and catalytic characteristics make them promising candidates for applications in energy storage, sensors, catalysis, environmental remediation, biomedical devices, and high-frequency electronics. Among various nanomaterials, spinel ferrites with the general formula MFe_2O_4 (M = divalent metal ion) have emerged as an important class of magnetic oxides due to their excellent chemical stability, low eddy current losses, high electrical resistivity, and tunable magnetic properties. These characteristics originate from the distribution of metal cations between tetrahedral (A) and octahedral (B) sites in the spinel crystal structure[2].

Cobalt ferrite (CoFe_2O_4) is one of the most technologically important hard magnetic spinel ferrites because of its high magnetocrystalline anisotropy, moderate saturation magnetization, excellent mechanical hardness, corrosion resistance, and thermal stability[3]. These properties make CoFe_2O_4 suitable for magnetic recording media, permanent magnets, microwave devices, ferrofluids, gas sensors, and electromagnetic interference shielding. Nevertheless, the intrinsic properties of cobalt ferrite can be further tailored through controlled cation substitution, which modifies the cation distribution, super-exchange interactions, crystallite size, and lattice parameters[4]. Among various dopants, Ga^{3+} and Al^{3+} ions are particularly attractive due to their non-magnetic nature and ionic radii comparable to Fe^{3+} , enabling their incorporation into the spinel lattice without disrupting the crystal structure[5]. Simultaneous substitution of Ga^{3+} and Al^{3+} for Fe^{3+} offers an effective strategy to engineer the structural and magnetic characteristics by regulating cation occupancy at the octahedral and tetrahedral sites. Such co-substitution is expected to influence lattice distortion, crystallinity, particle morphology, and magnetic exchange interactions, thereby providing an additional degree of control over the material properties[6].

In the present work, $\text{CoFe}_{2-2x}\text{Ga}_x\text{Al}_x\text{O}_4$ ($x = 0.1$ and 0.3) nanoparticles were synthesized via the sol–gel auto-combustion method, and their structural and morphological properties were systematically investigated using X-ray diffraction (XRD) and transmission electron microscopy (TEM).

2. Experimental Details

2.1 Synthesis of $\text{CoFe}_{2-2x}\text{Ga}_x\text{Al}_x\text{O}_4$ samples ($x = 0.1$ and 0.3)

$\text{CoFe}_{2-2x}\text{Ga}_x\text{Al}_x\text{O}_4$ samples ($x = 0.1$ and 0.3) nanoparticles were synthesized by the sol-gel auto-combustion method. Stoichiometric amounts of cobalt nitrate, ferric nitrate, gallium nitrate, and aluminium nitrate were dissolved in deionized water and stirred to obtain a homogeneous solution. The pH was adjusted to ~ 7 using ammonia solution, followed by heating at $80\text{--}90^\circ\text{C}$ to form a viscous gel. The gel underwent self-combustion, yielding a fluffy precursor powder, which was ground and calcined at $600\text{--}800^\circ\text{C}$ in air for several hours to obtain single-phase spinel $\text{CoFe}_{2-2x}\text{Ga}_x\text{Al}_x\text{O}_4$ nanoparticles. The synthesized powders were subsequently characterized for their structural, morphological, magnetic, and surface properties.

2.2 Materials Characterizations

The synthesized nanoparticle series was comprehensively characterized to investigate its structural, morphological, optical, surface, and magnetic characteristics. Phase identification and crystallite size analysis were carried out using X-ray diffraction (XRD) with a Bruker D8 Advance diffractometer. Surface morphology was examined through transmission electron microscopy (TEM).

3. Result and Discussion

The XRD patterns of the XRD spectra of $\text{CoFe}_{2-2x}\text{Ga}_x\text{Al}_x\text{O}_4$ samples ($x = 0.1$ and 0.3) confirm the successful formation of a single-phase cubic spinel ferrite structure without any detectable impurity peaks, as shown in **Figure 1**. The prominent diffraction peaks indexed to the (220), (311), (222), (400), (422), (511), and (440) planes agree well with the characteristic spinel phase, indicating high crystallinity. The (311) reflection exhibits the highest intensity, confirming its preferred orientation[7]. Increasing the Ga and Al substitution from $x = 0.1$ to 0.3 does not alter the crystal structure but causes slight variations in peak intensity and position, suggesting successful incorporation of Ga^{3+} and Al^{3+} ions into the CoFe_2O_4 lattice with minimal lattice distortion.

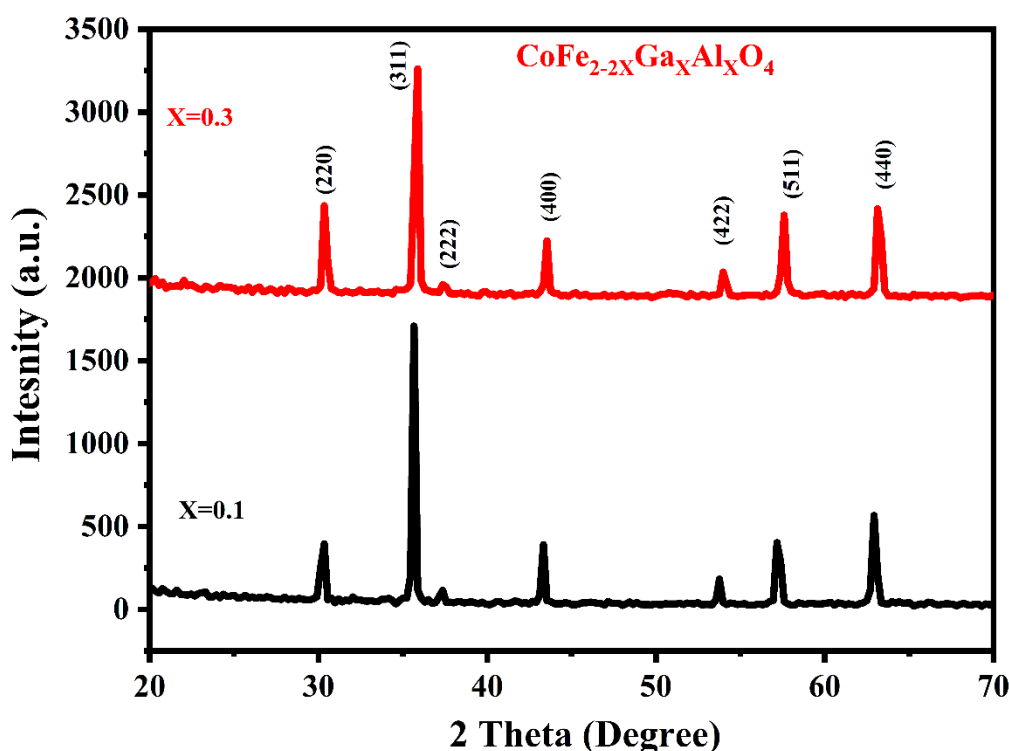


Figure 1 XRD spectra of $\text{CoFe}_{2-2x}\text{Ga}_x\text{Al}_x\text{O}_4$ samples ($x=0.1$ and 0.3).

TEM images of $\text{CoFe}_{2-2x}\text{Ga}_x\text{Al}_x\text{O}_4$ nanoparticles for **Figure 2** (a) $x = 0.1$ and (b) $x = 0.3$ reveal the formation of nearly spherical to slightly irregular nanoparticles with noticeable agglomeration, which is commonly observed in ferrite nanomaterials due to their magnetic interactions and high surface energy. The particles are distributed

in the nanometre range, with sizes of approximately 40–70 nm, consistent with the XRD results. As the Ga–Al substitution increases from $x = 0.1$ to 0.3, the particles appear more uniformly distributed while maintaining a similar morphology. No distinct secondary phases or structural defects are observed, indicating that Ga^{3+} and Al^{3+} ions are successfully incorporated into the CoFe_2O_4 spinel lattice without significantly affecting the particle morphology.

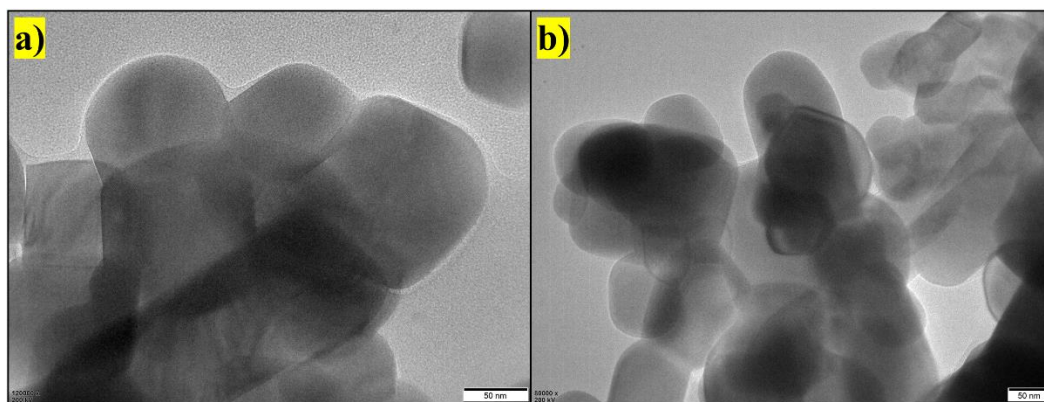


Figure 2 TEM image of $\text{CoFe}_{2-2x}\text{Ga}_x\text{Al}_x\text{O}_4$ a) $X=0.1$ and b) $X=0.3$.

4. Conclusion

$\text{CoFe}_{2-2x}\text{Ga}_x\text{Al}_x\text{O}_4$ ($x = 0.1$ and 0.3) nanoparticles were successfully synthesized by the sol–gel auto-combustion method. XRD analysis confirmed the formation of a highly crystalline single-phase cubic spinel structure without secondary phases, indicating successful incorporation of Ga^{3+} and Al^{3+} ions into the CoFe_2O_4 lattice. TEM observations revealed nearly spherical nanoparticles with slight agglomeration and particle sizes ranging from approximately 40 to 70 nm. Increasing the Ga–Al substitution preserved the spinel structure while improving particle uniformity. These findings demonstrate that Ga–Al co-substituted cobalt ferrite nanoparticles possess desirable structural and morphological characteristics for advanced magnetic and multifunctional nanomaterial applications.

5. References

- [1] S. Hussain, I. Chandio, M.A. Rashid, I. Sadiq, J.A. Baig, S.A. Solangi, M. Shahbaz, K.H. Thebo, Synthesis of nano-ferrites-based materials: A new paradigm for electrochemical sensors, *Journal of Environmental Chemical Engineering*, 13 (2025) 120218.
- [2] H. Qin, Y. He, P. Xu, D. Huang, Z. Wang, W. Han, Z. Wang, Y. Zhao, Q. Tian, C. Wang, Spinel ferrites (MFe_2O_4): Synthesis, improvement and catalytic application in environment and energy field, *Advances in Colloid and Interface Science*, 294 (2021) 102486.
- [3] A. Bachacheri, H. Nikmanesh, F. Doryani, High-coercivity $\text{CoCr}_{0.6}\text{Fe}_{1.4}\text{O}_4$ nanoparticles prepared by hydrothermal route for advanced multifunctional applications, *Scientific Reports*, 16 (2026) 18112.
- [4] P.C. Patil, A.A. Gaikwad, V.P. Phase, R.H. Kadam, S.E. Shirsath, J.J. Chamargore, Rare earth Ce and Y cation co-substitution and its effects on the strain, elasticity, and magnetism of Co–Zn ferrite nanomaterials, *Ceramics International*, 51 (2025) 21675–21688.
- [5] H. Shashanka, S. Saha, K. Haritha, A. P N, C. Ramana, Aluminum and Zinc Co-substituted Cobalt Ferrite: Structural, Magnetic, and Magnetostrictive Properties, *The Journal of Physical Chemistry C*, 127 (2023).
- [6] A. Rai, A.K. Thakur, Influence of co-substitution driven property tailoring in lanthanum orthoferrites (LaFeO_3), *Ceramics International*, 43 (2017) 13828–13838.
- [7] A.A. Ibiyemi, O. Akinrinola, G.T. Yusuf, Photoelectric and optoelectronic effects of hard ferromagnetic manganese cobalt (Mn–Co) ferrite nanoparticles for high-frequency device application, *Applied Physics A*, 128 (2022) 792.