Effects of Cu substitution and ^{60}Co gamma irradiation on the magnetic response of Co-Cu nanoferrites

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1. Introduction

Co–Cu ferrites, generally represented as $Co_{1-x}Cu_xFe_2O_4$ (x = 0.0, 0.25, 0.50, 0.75, and 1.0), are technologically important spinel oxides whose structural, magnetic, and hyperfine properties can be controlled through cation substitution. $CoFe_2O_4$ is a magnetically hard ferrite with relatively high saturation magnetization, remanent magnetization, coercivity, and magnetocrystalline anisotropy. In contrast, $CuFe_2O_4$ generally exhibits lower magnetization because Cu^{2+} has a lower magnetic moment and weaker magnetocrystalline anisotropy than Co^{2+}. Moreover, the Jahn–Teller activity of Cu^{2+} can distort the local octahedral environment and modify magnetic interactions within the spinel lattice.

Gamma irradiation provides an additional post-synthesis route for modifying ferrite properties. The interaction of gamma rays with the material can generate lattice defects, change the local cation environment, and alter magnetic exchange interactions without changing the nominal chemical composition. In this study, the combined effects of Cu substitution and gamma irradiation on the structural, vibrational, magnetic, and hyperfine properties of $Co_{1-x}Cu_xFe_2O_4$ nanoferrites were systematically investigated.

2. Methods and Results

$Co_{1-x}Cu_xFe_2O_4$ nanoferrites, including $CoFe_2O_4$ and $CuFe_2O_4$, were synthesized using the auto-combustion method. For each composition, the prepared powder was divided into five portions of approximately equal mass. One portion was retained as the unirradiated control (0 kGy), while the remaining portions were exposed to gamma radiation at absorbed doses of 50, 100, 200, and 500 kGy. Gamma irradiation was performed using a ^{60}Co gamma-ray source at the high-level gamma-ray irradiation facility of the Advanced Radiation Technology Institute (ARTI), Korea Atomic Energy Research Institute (KAERI), Jeongeup, Republic of Korea. Before irradiation, each powder sample was placed in a polyethylene container and sealed to prevent contamination and sample loss.

X-ray diffraction was employed to identify the crystalline phases and evaluate the crystallite size, lattice parameters, strain, and irradiation-induced structural modifications. Raman spectroscopy was used to investigate the characteristic vibrational modes of the spinel lattice and changes in local symmetry and cation–oxygen bonding. Magnetic hysteresis loops were measured using a vibrating sample magnetometer. The saturation magnetization (Ms), remanent magnetization (Mr), and coercivity (Hc) were determined from the hysteresis data. Mössbauer spectroscopy was further employed to examine the local Fe environments at the tetrahedral and octahedral sites, hyperfine magnetic fields, cation-site occupancy, and magnetic ordering.

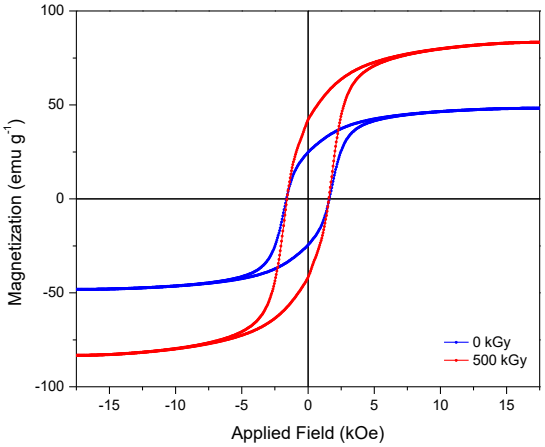


Fig. 1. Magnetic hysteresis loops of $CoFe_2O_4$ samples before (0 kGy) and after gamma irradiation at 500 kGy.

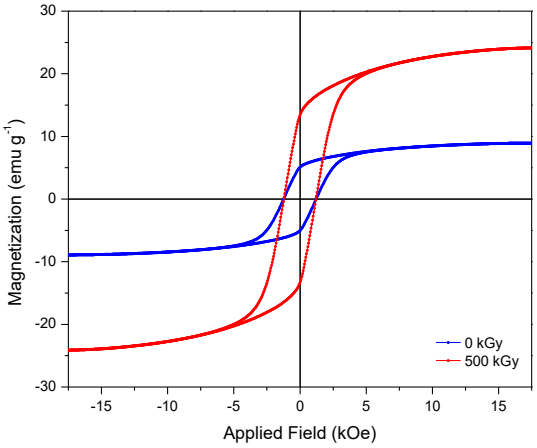


Fig. 2. Magnetic hysteresis loops of $CuFe_2O_4$ samples before (0 kGy) and after gamma irradiation at 500 kGy.

The magnetic measurements showed that Ms and Mr decreased with increasing Cu contents. Consequently, $CoFe_2O_4$ exhibited higher saturation and remanent magnetizations than $CuFe_2O_4$. This behavior is mainly attributed to the progressive replacement of strongly magnetic and highly anisotropic Co^{2+} ions by Cu^{2+} ions with a lower magnetic moment. Cu substitution can also modify the distribution of Fe^{3+} ions between the tetrahedral and octahedral sites and weaken the dominant A–O–B superexchange interactions. In addition, the Jahn–Teller distortion associated with octahedrally coordinated Cu^{2+} may alter the local crystal symmetry and magnetic coupling.

In contrast to the effect of Cu substitution, gamma irradiation increased Ms relative to the corresponding unirradiated samples. The hysteresis loops of $CoFe_2O_4$ showed a pronounced increase in magnetization after irradiation at 500 kGy. A comparison of the $CuFe_2O_4$ samples before and after irradiation also demonstrated an irradiation-dependent modification of their magnetic response. The enhancement of Ms following gamma irradiation may be associated with changes in lattice defects, crystallinity, local cation configurations, and the strength of the magnetic superexchange interactions. The XRD, Raman, and Mössbauer results provide complementary structural and microscopic information for correlating irradiation-induced changes with the macroscopic magnetic properties.

3. Conclusions

Cu substitution and gamma irradiation produced distinct and competing effects on the magnetic behavior of Co–Cu ferrites. Increasing the Cu content reduced Ms and Mr, whereas gamma irradiation enhanced Ms. These findings demonstrate that the magnetic properties of Co–Cu ferrites can be tailored through the combined control of chemical substitution and irradiation dose. The results also provide insight into the irradiation response of spinel ferrites and indicate their potential for radiation-resistant magnetic components, sensing systems, and other functional applications operating in radiation environments.

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