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Original Article

Dielectric Behaviour of Cd^{2+} Ions Substituted Ni-Cu Mixed Ferrites

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Abstract:

Ferrite specimens with the nominal composition $Ni_{0.5}Cu_{0.5-x}Cd_xFe_2O_4$ here $x = 0.0$, 0.2 and 0.4 were prepared by means of the conventional double-sintering ceramic process, using analytical-grade oxide powders as initial materials. X-ray diffraction (XRD) patterns noted at room temperature confirmed that all compositions crystallized in a mono-phase cubic spinel structure without detectable subordinate phases. The dielectric parameters were investigated as a function of frequency in the range of 100 Hz to 1 MHz using an LCR-Q meter. The obtained data reveal that the dielectric parameters exhibit higher values at low frequencies, decreases gradually as the frequency increases; the values then tend to level off, becoming almost frequency-independent at higher frequencies. This frequency-dependent response is explained by the fact that electron hopping between Fe^{2+} and Fe^{3+} ions cannot follow the rapidly oscillating electric field beyond a critical frequency. In addition, the parameters ε', ε'', and $\tan\delta$ were observed to increase with higher cadmium content (x).

Keywords: *Ni–Cu–Cd spinel ferrite, XRD, dielectric constant, dielectric loss, loss tangent.*

Introduction:

Ferrites materials are characterized by excellent magnetic and dielectric properties, making them useful for large range of technological applications such as transformers, antenna rods, filter circuits, memory devices, and components in communication systems [1]. Their high electrical resistivity, low eddy current and dielectric losses, moderate saturation magnetization, chemical stability, and economical preparation make them particularly attractive for industrial use. The physical and electrical behavior of ferrites mostly depends on factors such as the amount and type of doping materials, the cation distribution among the tetrahedral (A) and octahedral [B] sites, synthesis method, and sintering environment [2-4]. The dielectric parameters of ferrites are also strongly affected by the preparation technique, grain morphology, composition and their variation. Among spinel ferrites, nickel ferrite has gained particular attention owing to its inverse spinel nature, high Curie temperature, substantial magnetization, and chemical robustness. Among the spinel ferrites, due to distinguished properties such inverse spinel nature, high Curie temperature and substantial magnetization nickel ferrite has gained particular attention. Very few studies on cadmium substituted nickel-copper ferrite are reported in the literature. Here, we report our conclusions on dielectric studies of series Ni0.5Cu0.5-xCdxFe2O4 for x = 0.0, 0.2, 0.4 specimens.

Experimental:

Samples of series $Ni_{0.5}Cu_{0.5-x}Cd_xFe_2O_4$ here x = 0.0, 0.2, 0.4 was successfully created using the conventional double-sintering ceramic route [5]. High-purity analytical reagent (A.R.) grade oxides — NiO, CuO, CdO, and Fe_2O_3 — were accurately weighed in their stoichiometric ratios and thoroughly mixed in an agate mortar for around four hours to ensure uniformity. The homogenized combinations were initially pre-sintered at 1293 K for 12 hours. The samples were then permitted to cool slowly to room temperature. The pre-sintered powders were reground to achieve fine and homogeneous particle sizes, followed by a second sintering step at 1353 K for 14 hours to enhance crystallinity. The sintered powders were subsequently compacted into cylindrical pellets with a diameter of approximately 10 mm by applying a pressure of 6 tons per square inch using a hydraulic press. These pellets were finally sintered at 1273 K for 12 hours and furnace-cooled to room temperature to achieve dense, well-sintered specimens. Phase formation and physical categorization of the samples were examined using X-ray diffraction (XRD) over a 2θ range of 20°–80°at room temperature to confirm the mono-phase spinel structure. For dielectric parameter measurements, two sides of every pellet were layered by silver paste to ensure good ohmic contact. Dielectric parameters (ε', ε'', and $\tan\delta$) were noted at room temperature over a frequency range of 100 Hz to 1 MHz using an LCR-Q meter.

Results And Discussion:

3.1 X-Ray Diffraction (XRD) Analysis

The X-ray diffraction (XRD) configurations of series $Ni_{0.5}Cu_{0.5-x}Cd_xFe_2O_4$ (x = 0.0, 0.2, and 0.4) indicate that all specimens crystallize in a mono-phase cubic spinel structure, with no subordinate phases detected. Figure 1 presents a typical XRD pattern for the specimen with x = 0.2, showing sharp and well-defined Bragg peaks, indicative of good crystallinity.

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The lattice parameter, calculated from the XRD data, increases systematically with higher cadmium substitution. This expansion in lattice constant can be attributed to the ionic radius difference among the substituting cations—Ni^{2+} (0.69 Å), Cu^{2+} (0.72 Å), and Cd^{2+} (0.97 Å) [6]. Since Cd^{2+} possesses a relatively larger ionic radius than Cu^{2+}, its incorporation leads to a noticeable increase in lattice dimensions, confirming successful substitution at the appropriate sites in the spinel matrix.

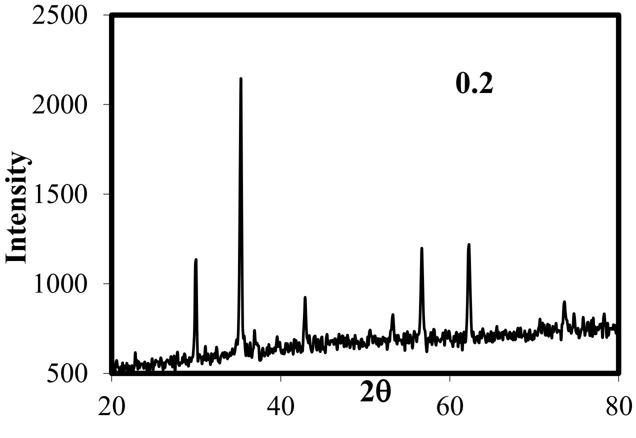

Fig. 1: *Typical* X-ray diffraction *Pattern of* $Ni_{0.5}Cu_{0.5-x}Cd_xFe_2O_4$ *(x=0.2)*

3.2 Dielectric Constant (ε′)

Figure 2 shows frequency-dependent performance of the dielectric constant (ε′) for all compositions. It is understood that ε′ rises with increasing cadmium content (x), whereas it declines with higher frequencies. This trend can be understood in terms of space charge polarization and the Maxwell–Wagner interfacial polarization model [7, 8]. In Ni–Cu–Cd ferrites, Cu^{2+} ions are distributed over both In the spinel structure, Cu^{2+} ions are distributed between the tetrahedral (A) and octahedral (B) sites, while Cd^{2+} ions mainly occupy the A sites and Ni^{2+} ions preferentially occupy the B sites. Substituting Cd^{2+} for Cu^{2+} leads to a redistribution of Fe^{3+} and Fe^{2+} ions between the A and B sites to maintain charge neutrality. This enhances the electron hopping between Fe^{3+} and Fe^{2+} ions, this results in enhanced polarization, leading to a higher dielectric constant. At lower frequencies, polarization can follow the applied alternating field, resulting in relatively high ε′ values. With increasing frequency, the polarization fails to keep pace with the field, leading to a significant reduction in ε′. At sufficiently high frequencies, the polarization mechanism ceases to respond, making ε′ almost frequency-independent. This frequency-dependent behaviour aligns well with earlier findings by other researchers [9–11].

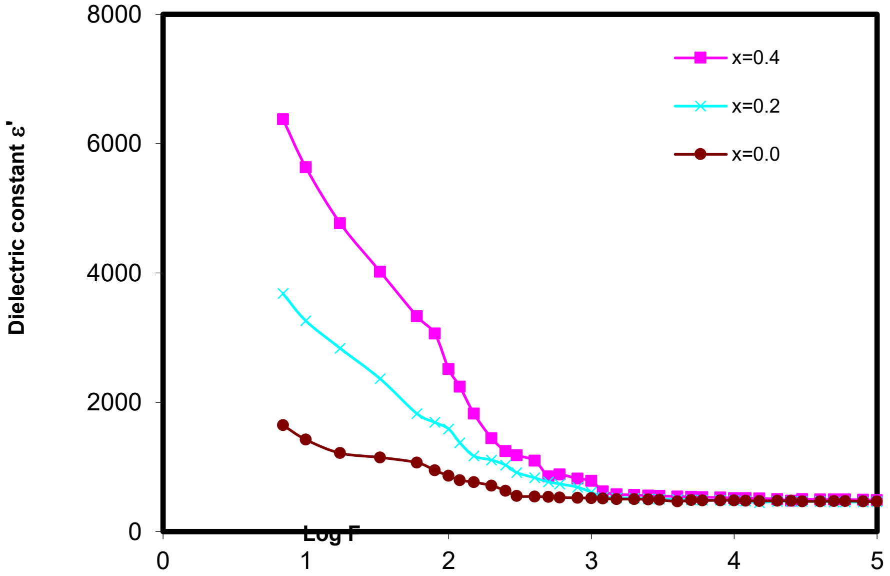

Fig.2: *Variation of* ε' *with Log F of* $Ni_{0.5}Cu_{0.5-x}Cd_xFe_2O_4$

3.3 Dielectric Loss (□□):

Figure 3 shows frequency dependency of dielectric loss (ε″) for all spacimens . It is observed that ε″ steadily drops with growing frequency and ultimately reaches a closely constant value at upper frequencies. This performance can be clarified by Maxwell–Wagner interfacial polarization and Koop's phenomenological theory [12]. At the lesser frequencies, the higher dielectric loss is due to interfacial polarization, which happens due to well-conducting grains being parted by unwell conducting grain boundaries. The charge carriers experience greater resistance at grain boundaries, causing energy dissipation, which manifests as dielectric loss. As frequency increases, the charge carriers are unable to follow the rapidly alternating field, resulting in reduced polarization and consequently lower dielectric loss.According to Rabinkin and Novikova [13], the polarization mechanism in ferrites is similar to electronic conduction, where localized electron hopping between Fe^{2+} and Fe^{3+} ions contributes to polarization. The high ε″ values at low frequencies are therefore due to defects such as oxygen vacancies, dislocations, and grain boundary irregularities [12–15].

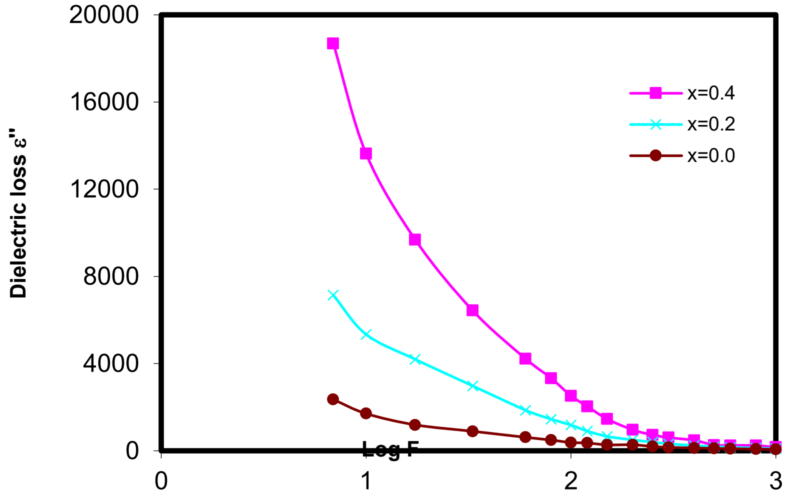

Fig.3: *Variation (ε'') with Log F of* $Ni_{0.5}Cu_{0.5-x}Cd_xFe_2O_4$

3.4 Dielectric Loss Tangent (Tan□):

The deviation of the dielectric loss tangent (tan δ) with frequency for all compositions is depicted in Figure 4. The observed initial decrease in tan δ as frequency increases can be interpreted using Koop's model [14], which describes the dielectric behaviour in terms of conducting grains separated by insulating grain boundaries. The magnitude of tan δ is influenced by several factors including stoichiometry, Fe^{2+} concentration, structural uniformity, and sintering temperature. [15, 16].

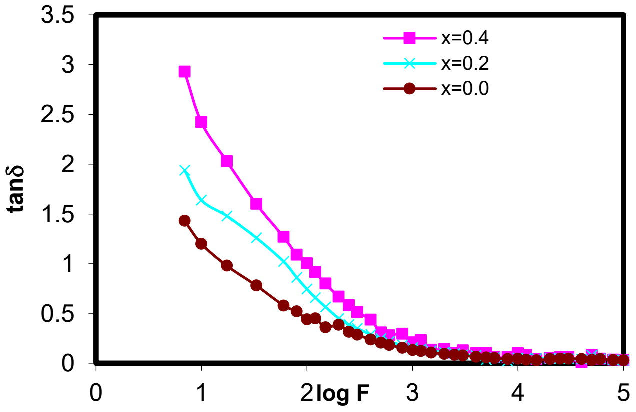

Fig.4: *Variation of tan□ with of(Log F of*$Ni_{0.5}Cu_{0.5-x}Cd_xFe_2O_4$

At lower frequencies, the higher tan δ values are due to lagging polarization and enhanced conduction losses, while at higher frequencies, the inability of dipoles to follow the alternating field leads to reduced losses. A comparison of dielectric parameters (ε′, ε″, and tan δ) at 100 Hz and 1 MHz is given in Table 1. It is evident that all three parameters increase with cadmium concentration but decrease as frequency increases, confirming the typical dielectric relaxation behaviour of ferrite systems.

Table: 1 Dielectric parameter (ε′), (ε″) and (tan□□ at
100 Hz and 1 MHz of $Ni_{0.5}Cu_{0.5-x}Cd_xFe_2O_4$ at room temperature

x	Frequency					
	100(MHz)			1(MHz)		
	□'	□"	tan□	□'	□"	tan□
0.0	862	379	0.44	494	0.64	0.0013
0.2	2035	1839	0.88	508	3.85	0.0075
0.4	2864	3509	1.08	551	4.23	0.0089

Conclusions:

- The Polycrystalline specimens x = 0.0, x = 0.2 and x = 0.4 of series $Ni_{0.5}Cu_{0.5-x}Cd_xFe_2O_4$ were prepared using the ceramic route, and single-phase cubic spinel crystallized structure verified by X-ray diffraction study successfully.
- The replacement of Cu^{2+} ions by Cd^{2+} ions shows improvement in the dielectric properties system, which can be accredited to enhanced Fe^{2+}–Fe^{3+} electron hopping and enlarged space-charge polarization. The dielectric parameters (ε′), (ε″), and (tan δ) exhibit high values at low frequencies and progressively decrease with increasing frequency, ultimately becoming nearly frequency-independent at higher ranges.
- The observed dielectric response is satisfactorily explained by Maxwell–Wagner interfacial polarization in conjunction with Koop's phenomenological approach.
- The observed frequency and compositional dependence of dielectric parameters suggest that Cd^{2+}-substituted Ni–Cu ferrites can be considered promising candidates for high-frequency device applications.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the of this paper

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