Effect of Cadmium doping on Structural and Magnetic Studies of Co-Ni Ferrites

Akshay B. Kulkarni¹*, Shridhar N. Mathad²
¹Department of Physics, S.K.E. S’s Govindram Seksaria Science College, Belagavi, 590006, India
²Department of Physics, K.L.E. Institute of Technology, Hubballi, 580030, India

Abstract:
We report effect of influence of Cd²⁺ ions on Co-Ni ferrites synthesized by the solid state reaction method. The X-ray diffraction analysis confirmed the cubic spinel phase with crystallite size varies between 20-24 nm. The SEM images show tetrahedral, octahedral, granular, long bulgy structures with variety of sizes. The Raman spectra for samples with x = 0.1 and x = 0.4 shown peaks corresponding to A₁g, E₂g and T₄g which very closely match with NiFe₂O₄ spectra with slight variation in peak position as an effect of different chemical formula. Magnetic measurements were carried out at room temperature. It is found that substitution influenced the magnetic properties. Saturation magnetization decreased from 52.74 to 32.68 emu.gm⁻¹ and coercivity shown an initial increase and then a continuous decrease, with increase in the Cd²⁺ substitution. Retentivity is found to be varying between 10.1 emu/gr - 6.21 emu/gr.

Keywords: Co-Ni ferrites; Magnetic properties; FTIR characterization; Raman spectra; SEM images.

1. Introduction

The ferrites have been studied extensively because of their technological applications. For applications related to high-frequencies, low eddy current loss is of primary importance. Ferrites are particularly good for high-frequency applications because of their high resistivity [1]. In fact, the ferrites with very high resistivity in bulk state make them useful magnetic material for application at microwave frequencies [2]. The cation distribution among these sites deeply affects the physical characteristics of spinel ferrites [3].

Spinel ferrites are important class of magnetic materials because to their wide range of applications in many areas. Ni-Zn ferrites is important class spinel magnetic material due to the simple and stable fabrication process, mechanical hardness, chemical/thermal stability, high resistivity, and high Curie temperature. Therefore, these ferrites are always the focus for technology and research purposes. It has also been reported that Ni₀.₅Zn₀.₅Fe₂O₄ ferrites has higher specific saturation magnetization as compared to other Ni-Zn ferrite compositions [4]. The nickel ferrite having high electrical resistivity for attaining low eddy current losses and enhanced magnetic properties for applications, made a material of choice particularly in the radio frequency region [5]. The cobalt ferrite draws close attention in research due to its remarkable physicochemical stability [6] and extensive applications in electronic devices [7], videotape and high-density recording disks [8-9], magnetic drug delivery [10]. For CoFe₂O₄, a typical inverse spinel ferrite, Fe³⁺ ions are located in the tetrahedral (A) and octahedral (B)

*) Corresponding author: akshayk.kud@gmail.com; physicssiddu@kleit.ac.in
sites and Co$^{2+}$ ions are located in octahedral sites only [11]. Cobalt and nickel ferrite materials are a subject of research, extensively due to important magnetic properties like, high coercivity, good remnant magnetization, moderate saturation magnetization and magnetic anisotropy. They also exhibit high electrical resistivity very good thermal and chemical stability [12-13]. Based on these properties the ferrites are used in many diverse range important application such as magnetic permanent magnets [14], transformer core [15], magnetic tape [16], data storage [17], radiofrequency circuits and high quality filters [18], high frequency integrated inductors [19], magnetic resonance imaging [20] controlled drug delivery [21] gas sensors [22] microwave absorbing paints [23], catalysis [24-25], and hybrid super capacitors [26].

The synthesis route, chemical composition, heat treatment, sintering temperature, type of element doped and processing condition impact the properties and grain size of the synthesized ferrite material [27]. For preparation of ferrites, several synthesis routes such as electron beam curing [28], solid state reaction method [29], sol-gel [30], co-precipitation [31-32], hydrothermal [33], high energy ball milling [34], green synthesis [35], thermal treatment [36], auto-combustion and microwave [37] have been used in the past.

In spite of enormous work on the substitution in spinel ferrites, less attention has been paid to substitution of cadmium ion into Co-Ni ferrites. In this work we synthesized the cadmium substituted Co-Ni ferrites synthesized by solid state reaction method and the structural and magnetic properties were studied using XRD, FTIR, SEM, Raman and VSM analysis.

2. Materials and Experimental Procedures

![Schematic diagram of synthesis of ferrite samples by solid state reaction method.](image)

All of the starting materials CoCl$_2$.6H$_2$O, NiCl$_2$.6H$_2$O, FeCl$_3$.6H$_2$O, and CdCl$_2$.H$_2$O were of analytical grade (Molychem) used for the synthesis of (Co$_{0.5}$Ni$_{0.5}$Cd$_{1.5}$Fe$_{2-x}$O$_4$) series samples by standard solid state reaction method (shown in Fig. 1). The chemicals are taken in
stoichiometric proportion and the mixture of chemicals is finely powdered and thoroughly mixed in an agate mortar, a few drops of distilled water is used as media for better uniformity. The mixture is heated in a muffle furnace (Meta lab Scientific Industries Mumbai) at 800 °C for 4 hours [38-39]. The chemical reaction is given below.

\[
CoCl_2 \cdot 6H_2O + NiCl_2 \cdot 6H_2O + FeCl_2 \cdot 6H_2O + CdCl_2 \cdot H_2O \rightarrow Co_{0.5}Ni_{0.5}Cd_{1.5x}Fe_{2-x}O_4 + nH_2O \uparrow + nCl_2 \uparrow
\]

Structural characterization of the ferrite powders is carried out; the X-ray diffraction patterns of the samples have been obtained on Bruker AXS D8 Advance Diffractometer (XRD), (with Cu-Kα radiation, wavelength, \( \lambda = 1.5406 \) Å), the FTIR of the samples have been obtained on Thermo Nicolet, Avatar 370 and the SEM images of the samples have been obtained on JEOL Model JSM - 6390LV, RAMAN spectra of the samples is taken from Horiba Jobin Vyon, Model Lab Ram HR and VSM of samples is obtained from Lakeshore, Model: 7410 series.

3. Results and Discussion

3.1. Powder X-ray diffraction (XRD) studies

The identification of crystal structure for ferrite samples was performed using X-ray diffraction (XRD) studies. XRD patterns of the entire ferrite series annealed at 800 °C were recorded and XRD pattern of Co_{0.5}Ni_{0.5}Cd_{1.5x}Fe_{2-x}O_4 ferrites (x = 0.0, 0.1, 0.2, 0.3, 0.4 and 0.5) series is shown in Fig. 2.

![Fig. 2. XRD comparative intensity plot for Co_{0.5}Ni_{0.5}Cd_{1.5x}Fe_{2-x}O_4 series with x = 0.0, 0.1, 0.2, 0.3, 0.4, 0.5.](image)

The positions and relative intensities of all identifiable peaks matched well with those from the standard JCPDS card no. 00-022-1086. The reflections observed from the planes (111), (220), (311), (222), (400), (422), (511), (440) and (533) for the samples confirm the
formation of a cubic spinel structure. The cubic spinel structure has Fd3m space group symmetry. The crystallite size of ferrite samples was calculated by using Debye-Scherer equation [38-39] $D = \frac{0.9 \cdot \lambda}{\beta \cdot \cos \theta}$ where $D$ is the crystallite size, $\beta$ is pure diffraction broadening given by the full width half maximum (FWHM) of the peaks, $\lambda$ is the wavelength of the radiation used, $\theta$ is the angle of diffraction. The average crystallite size for the ferrite series found to be 20–25 nm. The lattice parameter of all the samples was calculated using $a = \sqrt{\frac{a^2 + b^2 + c^2}{2}}$ and the values are given in Table I. The lattice parameter was found to increase with increasing Cd$^{2+}$ (8.35–8.36 Å), but for $x = 0.5$ the sample shown a shrinkage in the lattice constant (8.34 Å). The value of X-ray density ($\Delta x$) was determined using the following relation $\Delta x = \frac{8\cdot M \cdot N}{a^3}$ where $M$ represents the molecular weight of the sample, $N$ is Avogadro number and ‘$a$’ is the lattice parameter. It was found that the X-ray density, $\Delta x$ increased with increasing Cd$^{2+}$ concentration.

| Tab. I XRD peak intensities for Co$_{0.5}$Ni$_{0.5}$Cd$_{1.5x}$Fe$_{2-x}$O$_4$ series with $x = 0.0, 0.1, 0.2, 0.3, 0.4, 0.5$ and calculated lattice parameter values. |
|---|---|---|---|---|---|---|
| $h\ k\ l$ | Standard intensity | Observed Intensity | Observed Intensity | Observed Intensity | Observed Intensity | Observed Intensity |
| 1 1 1 | 10 | 10.9 | 9.6 | 11.2 | 10.9 | 11.1 | 10.5 |
| 2 2 0 | 30 | 28.3 | 28.8 | 30 | 30.5 | 29.2 | 29.3 |
| 3 1 1 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 2 2 2 | 8 | 10.1 | 11.4 | 15.5 | 12.5 | 17.2 | 10.8 |
| 4 0 0 | 20 | 21.3 | 21.3 | 22.7 | 18.6 | 22.9 | 22.9 |
| 4 2 2 | 10 | 10.4 | 8 | 9.1 | 7.8 | 8.6 | 9.3 |
| 5 1 1 | 30 | 30.6 | 24.5 | 24.5 | 23.5 | 24 | 26.5 |
| 4 4 0 | 40 | 45.2 | 33.6 | 30.7 | 30.1 | 30.8 | 35.2 |
| 6 2 0 | 4 | 4.5 | 2.7 | 3.9 | 2.8 | 6.6 | 3.6 |
| 5 3 3 | 9 | 9.3 | 6.3 | 6.6 | 6.5 | 11.1 | 6.8 |
| Lattice Parameter | 8.3919 | 8.3536 | 8.3597 | 8.3616 | 8.3614 | 8.3632 | 8.3411 |

| Tab. II Calculated values of volume of x-ray density, stacking fault coefficient, crystallite size, dislocation density and micro strain. |
|---|---|---|---|---|---|
| $x$ | X-ray density $\Delta x$ (gr/cm$^3$) | Stacking fault coefficient $\alpha$ | Crystallite size $D$ (Å) | Dislocation Density $\rho_D$ | Micro Strain $\varepsilon$ |
| 0.0 | 5.3440 | 0.00043 | 235.23 | 1.9652E+15 | 0.00151 |
| 0.1 | 5.5889 | 0.00037 | 221.18 | 2.3272E+15 | 0.00163 |
| 0.2 | 5.8412 | 0.00083 | 205.35 | 2.8646E+15 | 0.00180 |
| 0.3 | 6.0981 | 0.00109 | 213.29 | 2.6313E+15 | 0.00172 |
| 0.4 | 6.3502 | 0.00326 | 236.47 | 1.8657E+15 | 0.00149 |
| 0.5 | 6.6589 | 0.00044 | 229.29 | 2.1473E+15 | 0.00157 |

The stacking fault coefficient was calculated using $\alpha = \frac{2\pi^2}{45\sqrt{3}} \left( \frac{2\theta}{\tan \theta_{hkl}} \right)$ showed a very small value. This shows that the peaks studied are in expected position and no unexpected dominant peak is observed. The Dislocation density $\rho_D = 1/D^2$ and micro-strain $\varepsilon = \beta \cos \theta / 4$ are also shown in Table II.
The volume of unit cell has shown expansion from $x = 0.0$ to $x = 0.4$, as the substituted Cd$^{2+}$ ions are larger as compared to that of Fe$^{3+}$. For $x = 0.5$ the unit cell shown a shrinkage.

The hopping length $L_A = a \times \sqrt{3}/4$, $L_B = a \times \sqrt{2}/4$, where, $L_A$ is hopping length (distance between magnetic ions) at site A (tetrahedral) and $L_B$ is hopping length at site B (Octahedral); the bond length $A-O = (u-1/4)a\sqrt{3}$, $B-O = (5/8-u)a$, where, $A-O$ is bond length between metal ion at A site and Oxygen, $B-O$ is bond length between metal ion at B site and Oxygen and $u$ is oxygen ion parameter taken as 0.381 for nickel ferrites [40]; ionic radii $r_A = (u-1/4)a\sqrt{3} - O^{2-}$, $r_B = (5/8-u)a - O^{2-}$, where, $r(O^{2-})$ is the radius of oxygen ion (1.35 Å); shown the increase with increase in doping, the values are tabulated in Table III.

### Tab. III Calculated values of volume of unit cell, hopping length, bond length and ionic radii.

| $x$  | Volume of unit cell $V$(e$^{-30}$) | $L_A$ (Å) | $L_B$ (Å) | A-O (Å) | B-O (Å) | $r_A$ (Å) | $r_B$ (Å) |
|------|----------------------------------|----------|----------|---------|---------|----------|----------|
| 0    | 582.945                          | 3.6172   | 2.9535   | 1.8954  | 2.0383  | 0.5454   | 0.6883   |
| 0.1  | 584.206                          | 3.6198   | 2.9556   | 1.8968  | 2.0398  | 0.5468   | 0.6898   |
| 0.2  | 584.615                          | 3.6207   | 2.9563   | 1.8972  | 2.0402  | 0.5472   | 0.6902   |
| 0.3  | 584.562                          | 3.6206   | 2.9562   | 1.8972  | 2.0402  | 0.5472   | 0.6902   |
| 0.4  | 584.939                          | 3.6213   | 2.9568   | 1.8976  | 2.0406  | 0.5476   | 0.6906   |
| 0.5  | 580.321                          | 3.6118   | 2.9490   | 1.8926  | 2.0352  | 0.5426   | 0.6852   |

### 3.2. Fourier transforms infrared (FT-IR) characterization

![FT-IR curves for Co$_{0.5}$Ni$_{0.5}$Cd$_{1.5x}$Fe$_{2-x}$O$_4$ series with $x=0.0$, 0.1, 0.2, 0.3, 0.4, 0.5.](image)

The FT-IR bands are assigned to the vibration of metal ions in the crystal lattice. FT-IR spectra were recorded for Co$_{0.5}$Ni$_{0.5}$Cd$_{1.5x}$Fe$_{2-x}$O$_4$ ferrites ($x = 0.0$, 0.1, 0.2, 0.3, 0.4 and 0.5)
annealed at 800 °C. It is well known that the cubic spinel have two absorption bands in the range of 400-600 cm\(^{-1}\) corresponding to tetrahedral and octahedral clusters. The higher frequency band (\(v_1\)) attributes to the tetrahedral site, where as the lower frequency band (\(v_2\)) corresponds to the octahedral site [41]. The FT-IR spectra of the ferrite series is shown in Fig. 3. The ferrite samples showed bands in the region of 550-600 cm\(^{-1}\) corresponding to octahedral stretching and the tetrahedral stretching vibration was observed below 400 cm\(^{-1}\), the observed peak values for different Cd\(^{2+}\) doping concentration are tabulated in Table IV. The FT-IR source is adjusted from 350 cm\(^{-1}\), hence the bands obtained are of little less accuracy with multiple splitting observed below 400 cm\(^{-1}\); but the existence of band is confirmed. The bands show an increase in peak value with increase in doping.

Tab. IV FT-IR peaks for Co\(_{0.5}\)Ni\(_{0.5}\)Cd\(_{1.5x}\)Fe\(_{2-x}\)O\(_4\) series with \(x = 0.0, 0.1, 0.2, 0.3, 0.4, 0.5\).

| \(x\) | \(v_1\) | \(v_2\) (multiple split band positions) |
|------|--------|----------------------------------------|
| 0.0  | 594.41 | 401.50 390.09 375.53 361.90 355.01 |
| 0.1  | 595.63 | 402.73 393.09 384.87 376.34 368.13 356.70 |
| 0.2  | 596.37 | 392.08 383.37 363.13 355.76 |
| 0.3  | 595.58 | 410.31 396.44 386.06 371.27 352.41 |
| 0.4  | 596.45 | 406.02 391.86 381.14 374.35 367.42 |
| 0.5  | 597.42 | 402.05 393.19 375.77 367.27 |

3.3. Scanning electron microscope (SEM) studies

Fig. 4. SEM images of Co\(_{0.5}\)Ni\(_{0.5}\)Cd\(_{1.5x}\)Fe\(_{2-x}\)O\(_4\) series with \(x = 0.0, 0.1, 0.2, 0.3, 0.4, 0.5\).
The surface morphology and microstructure of the samples \( \text{Co}_{0.5}\text{Ni}_{0.5}\text{Cd}_{1.5x}\text{Fe}_{2-x}\text{O}_4 \) ferrites (\( x = 0.0, 0.1, 0.2, 0.3, 0.4 \) and 0.5) series are shown in Fig. 4.

Having a closer look on the images, it can be viewed that the tetrahedral, granular, octahedral, long bulgy structures observed in the samples. However, the phenomenon of grain growth decreased with increase in doping but the coagulation is increased giving rise to more agglomeration. The wide variety of size distribution is observed in particles. The samples shown some Nano size particles, but as the samples are synthesized by solid state reaction method at a sintering temperature of 800 °C, most of particles are of micro-meter range. Grain size of samples decreased with increase in doping; this may be justified as the \( \text{Cd}^{2+} \) ions have bigger size than other ions, this may create more residual stress, which results into smaller sized grains [42]. The average crystallite sizes of the samples determined by X-ray diffraction are smaller in comparison to that of grain size revealed by SEM images. This difference is attributed to the fact that the morphology shown by SEM possesses the size of the secondary group of clusters originate by the combination of many crystallites. Moreover, the X-ray pure line broadening analysis is only because of single crystallite and not of the entire grains [42].

### 3.4. Raman spectroscopy analysis

![Raman spectra](image)

Fig. 5. Raman spectra of \( \text{Co}_{0.5}\text{Ni}_{0.5}\text{Cd}_{1.5x}\text{Fe}_{2-x}\text{O}_4 \) with a) \( x = 0.1 \) and b) \( x = 0.4 \).

| Sl. No. | Compound Vibrational Mode | Nickel Ferrites | \( x=0.1 \) | \( x=0.4 \) |
|--------|---------------------------|-----------------|------------|------------|
| 1.     | \( E_g \)                 | 339             | 351.019    | 351.019    |
| 2.     | \( T_{2g}(2) \)           | 490             | 475.012    | 486.533    |
| 3.     | \( T_{2g}(3) \)           | 579             | 545.763    |            |
| 4.     | \( A_{1g} \)              | 700             | 691.605    | 684.784    |

Tab. V Raman band frequencies and mode assignments for polycrystalline spinel powder of \( \text{Co}_{0.5}\text{Ni}_{0.5}\text{Cd}_{1.5x}\text{Fe}_{2-x}\text{O}_4 \) with \( x = 0.1, 0.4 \).

The Raman spectra of the samples \( \text{Co}_{0.5}\text{Ni}_{0.5}\text{Cd}_{1.5x}\text{Fe}_{2-x}\text{O}_4 \) ferrites (\( x = 0.1 \) and 0.4) are shown in Fig. 5. The spectra show three peaks for \( x = 0.1 \) (at 351 cm\(^{-1}\), 475 cm\(^{-1}\), and 691.6cm\(^{-1}\)) and five major peaks for \( x = 0.4 \) (at 351 cm\(^{-1}\), 486.5 cm\(^{-1}\), 545.7 cm\(^{-1}\), 684.7 cm\(^{-1}\) and 1070.2 cm\(^{-1}\)). The observed and reference peak values are tabulated in Table V. The peaks match with the Raman spectra of \( \text{NiFe}_2\text{O}_4 \) obtained by calcinations at 800 °C [43-44].
The ferrite samples have spinel structure and Fd3m space group symmetry. The factor group analysis predicts 5 Raman active internal modes [45],

$$A_{1g} + E_g + 3 T_{2g}$$

The synthesized samples are mixed ferrites. The sample with $x = 0.1$, show three corresponding peaks at 351 cm$^{-1}$, 475 cm$^{-1}$, and 691.6 cm$^{-1}$ for $A_{1g}$, $E_g$ and $T_{2g}$. The 351 cm$^{-1}$ corresponds to the $E_g$ mode, the 475 cm$^{-1}$ corresponds to $T_{2g}$ mode and 691.6 cm$^{-1}$ corresponds to $A_{1g}$. Whereas the sample with $x = 0.4$ show five peaks at 351 cm$^{-1}$, 486.5 cm$^{-1}$, 545.7 cm$^{-1}$, 684.7 cm$^{-1}$ and 1070.2 cm$^{-1}$. The 351 cm$^{-1}$ corresponds to the $E_g$ mode, the 486.5 cm$^{-1}$ and 545.7 cm$^{-1}$ corresponds to $T_{2g}$ (2) and $T_{2g}(3)$ symmetries, 691.6 cm$^{-1}$ corresponds to $A_{1g}$ and 1070.2 cm$^{-1}$ correspond to $D3d= A_{1g} + E_g$. The $x = 0.1$ and $x = 0.4$ shown an increase for wave numbers of the peaks for $T_{2g}$ and decrease for $A_{1g}$. The $T_{2g}(1)$ is having very weak intensity of the peak and hence is not observed in both the Raman spectra. The peak for $T_{2g}(3)$ is missing in $x = 0.1$ sample. The sample $x = 0.4$ shown a well intense $T_{2g}(3)$ peak. The Raman spectra of the samples conclusively give evidence of Fd3m symmetry and of the spinel structure of ferrite samples.

### 3.5. Magnetic properties

Fig. 6. Hysteresis curves of Co$_{0.5}$Ni$_{0.5}$Cd$_{1.5x}$Fe$_{2-x}$O$_4$ series with $x = 0.0, 0.1, 0.2, 0.3, 0.4, 0.5$. a) Up to 5000 Oe b) above 5000 Oe.

The Hysteresis loops for all the samples were recorded at room temperature using Vibrating sample magnetometer (VSM) by applying the external magnetic field between 0-15 kOe and are shown in Fig. 6. It was observed that the saturation magnetization $M_s$ decreased with increase in Cd$^{2+}$ ion concentration (Table VI). This behavior of saturation magnetization can easily be explained as the magnetic Fe$^{3+}$ ion is reduced in the lattice with increase in doping of a non-magnetic Cd$^{2+}$ ion as a replacement. The decrease in the saturation magnetization was attributed to the higher magnetic moment of Fe$^{3+}$ ion as compared to its substituted counterpart Cd$^{2+}$ ion. The saturation magnetization is observed to be increasing even at 15 kOe. The constant line in M-H curve depends on particle size and domain boundaries. If the particle size is smaller, the greater magnetic field required for orienting all particles. The reaching of complete saturation will be continued for very high applied magnetic field, sometimes even at 50 kOe the curve do not get completely saturated [42, 46]. As per the SEM images, the sample contains wide variety of shapes and sizes. The existence of Nano size particles is the reason for observation of non-saturation even at 15 kOe. On the
basis of Neel’s two sub-lattice model the magnetic moment in Bohr magneton \( n_B \) is given by 
\[
N(\chi) = M_B(\chi) - M_A(\chi),
\]
where \( M_B \) and \( M_A \) are magnetization of B and A sub-lattices, respectively [47]. The magnetic moment at A-sub lattice decreased with increase in the doping, which lead to the overall decrease in the magnetic moment of the samples. The values of saturation magnetization, coercivity and remanance are given in Table VI.

With increase in cadmium ion doping in the cobalt nickel ferrite, values of coercivity increased up to \( x = 0.2 \) and then decreased till \( x = 0.5 \). This behavior can be explained as, the lattice parameter increased attributing to increase in volume of unit cell, the energy required to orient such an individual group increases. But the increase in cadmium concentration reduced the grain size as per SEM images. The reduction in grain size reduces surface and grain boundary orientation energy and hence the coercivity value is reduced for higher values of doping.

Similar to coercivity, energy stored (area in hysteresis curve) in the samples initially increased from \( x = 0.0 \) to \( x = 0.2 \) then reduced till \( x = 0.5 \). The same reasons attribute to lapse in energy stored in magnetic hysteresis.

The ratio of retentivity to Magnetization \( M_r/M_s \) is around 0.2 (0.175 to 0.247). The retentivity is observed to be around 10 emu/gr, the lowest is for \( x = 0.5 \) shown 6.21 emu/gr, this may be due to lowest lattice parameter, highest dopant concentration which is paramagnetic in nature and low grain size of the particles. The retentivity showed a sudden dip near to magnetic field at 0 Oe. This is a unique observation, may be attributed to existence of mixture of two phases in the samples, one is of ferrimagnetic phase which is in major proportion and another of super paramagnetic phase which is of very small proportion. The dip is very low for low concentration of doping and increased with increased in doping. The material in super paramagnetic state will show zero retentivity at zero applied magnetic fields. As the field is reversed, orientation of super paramagnetic grains will change and they add up to existing magnetization, giving rise to a dip at \( x = 0 \) Oe.

| Tab. VI Values of coercivity, magnetization and retentivity from hysteresis curves of Co_{0.5}Ni_{0.5}Cd_{1.5}xFe_{2-x}O_{4} series with \( x = 0.0, 0.1, 0.2, 0.3, 0.4, 0.5 \). |
| Coercivity (Hc) Oe | 514.62 | 592.36 | 665.46 | 583.29 | 580.63 | 488.69 |
| Magnetization (Ms) emu/g | 52.743 | 46.305 | 40.886 | 38.615 | 38.294 | 32.686 |
| Retentivity (Mr) emu/g | 9.2264 | 9.4641 | 10.106 | 8.6569 | 8.0694 | 6.2163 |
| Mr/Ms | 0.175 | 0.204 | 0.247 | 0.224 | 0.211 | 0.190 |

4. Conclusion

The Cd doped Co-Ni ferrite (\( x = 0.0, 0.1, 0.2, 0.3, 0.4 \) and 0.5) particles are synthesized successfully by solid state reaction process. The XRD data showed that with Cd\(^{2+}\) concentration initial increase in the lattice constant (from \( x = 0.0 \) to \( x = 0.4 \)) but showed lattice shrinkage for \( x = 0.5 \). FTIR showed two peaks one around 600 cm\(^{-1}\) and another below 400 cm\(^{-1}\) corresponding to octahedral and tetrahedral sites of spinel structure. The XRD and FTIR confirm the single phase cubic spinel structure of the samples. The SEM images showing that the samples contain octahedral, tetrahedral, granular and long bulgy structures. Grain size found to decrease with doping and wide range of size of the grains is observed in the images. The Raman spectra showed three major peaks corresponding the \( E_g \), \( T_2g(2) \) and \( A_{1g} \) which are matching with expected positions confirming the \( f\bar{d}3m \) symmetry corresponding to cubic spinel structure. The VSM studies of samples showed coercivity in the range 500-600 Oe. The Cd doping resulted in an initial increase and then a decrease in net coercivity. The Magnetization and retentivity is found to decrease with increase in doping. Magnetization is
found to be in the range of 53-32 emu/gr. The retentivity to magnetization ratio is approximately 0.2 for all samples.

Acknowledgments

The authors would like to thank SAIF-STIC Cochin, UGC-DAE-CSIR Indore, and CIF-IIT Guwahati for providing analysis facility and all the laboratory staffs for their kind assistance.

5. References

1. S. Chikazumi, Physics of Ferromagnetism, second ed., Oxford University Press, UK, 2005.
2. A. Goldman, “Modern Ferrite Technology”, second ed., Springer Science Business Media, Inc., USA, 2006.
3. S. G. Doh, E. B. Kim, B. H. Lee, J. H. Oh, J. Magn. Magn. Mater., 272 (2004) 2238.
4. X. Wu, W. Wu, L. Qin, K. Wang, S. Ou, K. Zhou, Y. Fan, J. Magn. Magn. Mater., 379 (2015) 232.
5. K. Praveena, K. Sadhana, S. Bharadwaj, S. R. Murthy, J. Magn. Magn. Mater., 321 (2009) 2433.
6. P. Chirawatkul, S. Khoonsap, S. Phumying, C. Kaewhan, S. Pinitsoontorn, S. Maensiri, J. Alloys Comp., 697 (2017) 249.
7. F. Mazaleyrat, L.K. Varga, J. Magn. Magn. Mater., 215 (2000) 253.
8. M. A. Ahmed, A. A. El-Khawlani, J. Magn. Magn Mater., 321 (2009) 1959.
9. V. Pillai, D. O. Shah, J. Magn. Magn. Mater., 163 (1996) 243.
10. Y. Qu, H. Yang, N. Yang, Y. Fan, H. Zhu, G. Zou, Mater. Lett., 60 (2006) 3548.
11. M. Kooti, A. N. Sedeh, J. Mater. Sci. Technol., 29 (2013) 34–38.
12. T. Dippong, E. A. Levei, O. Cadar, F. Goga, L.B. Tudoran, G. Borodi, J. Anal. Appl. Pyrol., 128 (2017) 121.
13. T. Dippong, O. Cadar, E. A. Levei, C. Leostean, L.B. Tudoran, Ceram. Int., 43 (2017) 9145.
14. H. J. Kim, D. Y. Kim, J. P. Hong, IEEE Trans. Magn., 50 (2014) 1.
15. M. N. Akhtar, M. A. Khan, M. Ahmad, M. S. Nazir, M. Imran, A. Ali, A. Sattar, G. Murtaz, J. Magn. Magn. Mater., 421 (2017) 260.
16. M. A. Lantz, S. Furrer, et. al., IEEE Trans. Magn., 51 (2015) 1.
17. S. Thankakan, B. P. Jacob, S. Xavier, E.M. Mohammed, J. Magn. Magn. Mater., 348 (2013) 140.
18. H. M. Zaki, S. H. Al-Heniti, T. A. Elmosalami, J. Alloys Compd. 633 (2015) 104.
19. R. Anthony, N. Wang, D. P. Casey, C.O. Mathuna, J. F. Rohan, J. Magn. Magn. Mater., 406 (2016) 89.
20. J. Estelrich, E. Escribano, J. Queralt, M. A. Busquets, Int. J. Mol. Sci., 16 (2015) 8070.
21. G. S. Wang, Y. Y. Ma, Z. Y. Wei, M. Qi, Chem. Eng. J., 289 (2016) 150.
22. A. Šútka, K.A. Gross, Sens. Actuat. B: Chem., 222 (2016) 95.
23. L. Folgueras, M. Alves, M. Rezende, J. Aerospace Manage., 2 (2010) 63.
24. F. M. Moghaddam, G. Tavakoli, H. R. Rezvani, Catal. Commun., 60 (2015) 82.
25. T. Dippong, E. A. Levei, O. Cadar, A. Mesaros, G. Borodi, J. Anal. Appl. Pyrol., 125 (2017) 169.
26. S. Repp, E. Harputlu, S. Gurgen, M. Castellano, N. Kremer, N. Pompe, J. Womer, Hoffmann, R. Thomann, F. Emen, S. Weber, K.E. Peakoglu, Nano, 10 (2018) 1877.
27. S. K. Gore, S. S. Jadhav, V. V. Jadhav, S. M. Patange, M. Naushad, R. S. Mane, K. H. Kim, Sci. Rep., 7 (2017) 2524.
28. S. Zahi, M. Hashim, A.R. Daud, J. Magn. Magn. Mater., 308 (2007) 177.
29. S. L. Galagali, R. A. Patil, R. B. Adaki, C. S. Hiremath, S. N. Mathad, R. B. Puar, Sci. Sint., 50 (2018) 217.
30. A. Pradeep, P. Priyadharsini, G. Chandrasekaran, J. Magn. Magn. Mater., 320 (2008) 2774.
31. P. Kashid, M. Shedam, A. B. Kulkarni, S. N. Mathad, R. Shedam, J. Adv. Phy., 6 (2017) 1.
32. R. Vishwaroop, S. N. Mathad, Sci. Sint., 52 (2020) 349.
33. J. Maletaškić, M. Čebela, M. P. Đorđević, D. Kozlenko, S. Kichanov, M. Mitrić, B. Matović, Sci. Sint., 51 (2019) 71.
34. S. Torkian, A. Ghasemi, R. S. Razavi, Ceram. Int., 43 (2017) 6987.
35. N. M. Deraz, Sci. Sint., 52 (2020) 53.
36. V. K. Chakradharya, A. Ansari, M. J. Akhtara, J. Magn. Magn. Mater., 469 (2019) 674.
37. R. Shahraki, M. Ebrahimi, S. A. S. Ebrahimi, S. M. Masoudpanah, J. Mag. Mat., 324 (2012) 3762.
38. A. B. Kulkarni, S. N. Mathad, Int. J. Self-Prop. High-Temp. Synt., 27 (2018) 37.
39. A. B. Kulkarni, S. N. Mathad, Mater. Sci. Energy Tech., 2 (2019) 455.
40. A. T. Pathan, S. N. Mathad, A. M. Shaikh, Int. J. Self-Prop. High-Temp. Synt., 23 (2014) 112.
41. R. D. Waldron, Phys. Rev., 99 (1953) 1727.
42. H. S. Aziz, S. Rasheed, R. A. Khan, A. Rahim, N. Nisar, S. M. Shah, F. Iqbal, A. R. Khan, RSC Adv., 6 (2016) 6589.
43. A. Ahlawat, V. G. Sathe, V. R. Reddy, A. Gupta, J. Magn. Magn. Mater., 323 (2011) 2049.
44. A. Ahlawat, V. G. Sathe, J. Raman Spectrosc., 42 (2011), 1087.
45. P. R. Graves, C. Johnston, J. J. Campaniello, Mat. Res. Bull., 23 (1988) 1651.
46. D. Carta, M. F. Casula, A. Falqui, D. Loche, G. Mountjoy, C. Sanggregorio, A. Corrias, J. Phys. Chem. C, 113 (2009) 8606.
47. M. A. Dar, K. Majid, M. H. Najar, R. K. Kotnala, J. Shah, S. K. Dhawan, M. Farukh, Phys. Chem. Chem. Phys., 19 (2017) 10629.

Сажетак: У овом раду представљамо утицај Cd2+ јона на синтезу Co-Ni ферита реакцијом у чврстом стању. Рендгенска дифракција је потврдила да величина кристалита кубичне спинелне фазе варира између 20 - 24 nm. SEM слике показују тетраедарску, октаедарску и грануларну структуру различитих димензија зрана. Раман спектри узорака са x = 0.1 и x = 0.4 показују пикове које одговарају Alg, Eg и T2g и који се блиско поклапају са спектром NiFe2O4. Магнетна својства су мерена на собној температури. Супституција утича на магнетна својства. Магнетна сатурација расте од 52.74 до 32.68 emu.gm-1 а коерцитивност показује почетни раст а затим константно опадање са порастом супституције јонима Cd2+. Задржавање варира између 10.1 emu/gr - 6.21 emu/gr.

Кључне речи: Co-Ni ферити; магнетна својства; ФТИР; Раман спектри, рендгенска дифракција, SEM слике.
© 2021 Authors. Published by association for ETRAN Society. This article is an open access article distributed under the terms and conditions of the Creative Commons — Attribution 4.0 International license (https://creativecommons.org/licenses/by/4.0/).