Structural Morphological and Infrared Properties of Cd$^{2+}$ Substitutes Nickel Ferrite Particles

B. H. Devmunde$^1$, P. S. Bhalerao$^2$, M. B. Solunke$^2$

$^1$Vivekanand Arts, Sardar Dalip Singh Commerce and Science College, Aurangabad-431005

$^2$Vasantrao Naik College, Airport Road, Aurangabad-431003

Corresponding author e-mail: bhdevmunde05@gmail.com

Abstract. The Structural properties of cadmium substituted nickel ferrite with general formula Ni$_{1-x}$Cd$_x$Fe$_2$O$_4$ (x=0.0, 0.1, 0.2, 0.3, 0.4 and 0.5) were synthesized by using Sol-gel auto combustion method. All the chemicals used for preparations was high purity (99.9% Sigma-Aldrich). The prepared nanoparticles samples were investigated by characterizing them through X-ray diffraction, scanning electron microscopy and infrared spectroscopy. From XRD results, it is observed prepared samples were in the nano size having cubic spinel structure with single phase. Lattice constant is found increasing with Cd$^{2+}$ concentration. The average grain size obtained from SEM in the range of 45-58 nm. The EDAX plot gives the evidence of presence of Ni$^{2+}$, Cd$^{2+}$, Fe$^{3+}$, and O$^{2-}$ ions with proper ratio confirming the desired stoichiometric composition. IR spectra exhibit two distinct absorption bands hear about 400 cm$^{-1}$ and 600 cm$^{-1}$.

1. Introduction

In recent years, the interest in investigations of nano-size materials have increased due to their remarkable physical and chemical properties which are often differ from the bulk counterpart[1]. The difference in properties of nano-size materials is attributed to increase in surface area to volume ratio, quantum confinement effect and energy band gap[2]. Nanocrystalline spinel ferrites possesses remarkable properties and wide practical and potential applications in the information storage system, ferrofluid technology, in the permanent magnets, microwave absorbers, chemical sensors, etc[3-6]. The spinel ferrite has general formula of MFe$_2$O$_4$, where M is any divalent ion of metals such as nickel, cadmium, zinc, magnesium, copper, etc. Structural, electrical, and magnetic properties of these materials effectively depend upon their stoichiometry, methods of synthesis, and sintering temperature[7, 8]. The unit cell of the spinel structure is obtained by doubling approximately face-centered cubic oxygen sublattice along each of the three directions of the resulting 64 tetrahedral [A] sites and 32 octahedral sites [B], only 8 and 16 are occupied, respectively, by cations in stoichiometric spinel. Among the spinel ferrites, the substitution of non-magnetic ions of Cd$^{2+}$ in nickel ferrite considered to be the most versatile and found wide spread application in the electronics and microwave devices, due to their high electrical resistivity, low eddy current and dielectric loss. CdFe$_2$O$_4$ possesses normal spinel structure and NiFe$_2$O$_4$ is completely inverse spinel structure, because Ni$^{2+}$ has a strong preference for the electrical conductivity octahedral site [B-site]. Cadmium is the
non-magnetic divalent ions which occupy essentially tetrahedral [A]-site, when substituted in ferrites. Ni–Cd ferrite, is a soft magnetic material, with a spinel crystal structure with wide spread applications in recording heads, antenna rods, loading coils, microwave devices, core material for power transformers due to their high resistivity and low eddy current losses[9-11]. According to literature report, the substitution of Cd$^{2+}$ in ferrite is wellknown to enhance the magnetic and electrical properties like saturation magnetization[12]. Also, the substitution of Cd$^{2+}$ brought some modifications in structural and electrical properties in Li-Ni ferrite[13]. A lot of work is being carried out on the electrical properties of spinel ferrites both in bulk and in nano form. B. H. Devmunde et al[14], studied the electrical properties of Cd substituted NiFe$_2$O$_4$. He found that substitution of Cd has significantly decreases resistivity with the increasing temperature, revealing the semiconducting nature of the prepared Ni-Cd samples. Curie temperature decreases from 860°C to 566°C with increase in Cd$^{2+}$ content. Thakur et al[15], studied the dielectric properties of Mn–Zn nano ferrites. They reported that the resistivity of the studied system has increased 100 times than those samples prepared by the conventional ceramic methods. Yue et al[16], studied the Ni–Cu–Zn nano ferrite system. They reported that the doping of Mn in formulation has largely affected the grain size and electromagnetic properties of the system. They also found that dielectric constant and dissipation factor are affected by the MnO$_2$ doping. Nath et al[17], have studied the magnetic orders in Ni-Cd ferrite. Nejati et al[18], have discussed the superparamagnetic nature of NiFe$_2$O$_4$ nanoparticles synthesized by hydrothermal method. Modi et al[19], have studied the pre and post annealing particle size of the Ni-Cd ferrite nanoparticles synthesized by wet-chemical technique. Binu et al[20], have studied structural and magnetic properties of Gd$^{3+}$ doped Ni-Cd mixed ferrites. Nikumbh et al[21], have studied the structural, electrical and magnetic properties and cation distribution of cadmium -substituted nickel ferrite.

According to the literature report and above discussion, very little work has been reported on Ni-Cd spinel ferrite and which is mostly synthesized by ceramic technique in bulk form, has been investigated by many workers. However, Ni-Cd ferrite prepared by sol-gel auto combustion method has not been investigated for structural, morphological and infrared properties. In this work, the effect of Cd$^{3+}$ substitution on structural, morphological and infrared properties of NiFe$_2$O$_4$ nanoparticles synthesized by sol gel-auto combustion technique were investigated.

2. Experimental details

2.1. Synthesis of Ni$_{1-x}$Cd$_x$Fe$_2$O$_4$ (0.0 ≤ x ≤ 0.6) nanoparticles

Nanocrystalline powders of Ni$_{1-x}$Cd$_x$Fe$_2$O$_4$ (x = 0.0, 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6) were synthesized by using sol gel auto-combustion method. All the chemicals were analytical grade purchased from Sigma-Aldrich with purities ≥ 99.9 % and were used without any further purification. In a typical synthesis procedure, nickel nitrate hexahydrate (Ni(NO$_3$)$_2$·6H$_2$O), cadmium nitrate hexahydrate (Cd(NO$_3$)$_2$·6H$_2$O), ferric nitrate nonahydrate (Fe(NO$_3$)$_3$·9H$_2$O), citric acid monohydrate (C$_6$H$_8$O$_7$·H$_2$O) were used as starting materials. Double distilled water was used as a solvent. According to the stoichiometric proportion of Ni$_{1-x}$Cd$_x$Fe$_2$O$_4$ (where x = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6), all the nitrates were separately dissolved in minimum amount of distilled water and stirred on magnetic stirrer for 20 minutes. All the solutions were mixed together and stirred on a magnetic stirrer until the nitrates were completely dissolved. The metal nitrate to citric acid ratio was taken as 1:3. The solutions were stirred with continuous stirring on magnetic stirrer; drop by drop ammonia solution was added to adjust the pH value to 7. Then the solution was heated on hot plate at 90 °C with constant stirring until gel was formed. Instantaneously gel ignites with the formation of large amount of gas, resulting in to light weight voluminous powder. The resulting precursor powder was annealed at 700 °C for 6 h to obtain Ni$_{1-x}$Cd$_x$Fe$_2$O$_4$ nano-crystalline material.

2.2. Characterizations

The powder X-ray diffraction (XRD) pattern for all the samples were recorded at room temperature on Philips X-ray diffractometer (Model PW3710) using Cu-Kα radiation (λ = 1.5406 Å). The surface morphological studies were carried out using scanning electron microscopy (SEM) using JEOL-JSM-
5600 scanning electron microscope. The stoichiometric proportion of the constituent of the prepared magnetic nano-particles was examined using energy dispersive analysis of X-ray (EDAX) technique attached with the SEM. The infrared spectroscopy (IR) spectra of all the calcined samples were recorded in the range of 1000-300 cm\(^{-1}\) IR-BRUKER-TENSOR 37- FTIR-ATR instrument. The IR spectrum is generally used to investigate the chemical and structural changes that take place during the combustion process and to reveal the mechanism of self-propagating combustion.

3. Results and discussion

3.1. X-ray diffraction (XRD)

X-ray diffraction (XRD) patterns for all synthesized samples are shown in Figure 1. X-ray diffraction analysis revealed that all the diffraction peaks seen in the XRD pattern well matches with the standard pattern of pure nickel ferrite (JCPDS No: 10-325). The analysis of XRD pattern revealed the formation of single phase cubic spinel structure. It is evident from Figure 1 that a small amount of impurity phases in the form of Fe\(_3\)O\(_4\) is present when x along with their corresponding interplanar spacing \((h k l)\) values, intensity and relative intensity ratio of the Ni\(_{1-x}\)Cd\(_x\)Fe\(_2\)O\(_4\) ferrite system with \(x = 0.0, 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6\). It is seen that the interplanar spacing \((d)\) values show gradual decrease with increasing Bragg’s angle for all the samples. The intensity of \((311)\) plane is more as compared to other planes like \((220), (222), (400), (422), (511)\) and \((440)\).

![Figure 1.XRD pattern of Ni\(_{1-x}\)Cd\(_x\)Fe\(_2\)O\(_4\) (x = 0.0, 0.1, 0.2, 0.3, 0.4, and 0.5) nanoparticles.](image)

The lattice constant \((a)\) values of the Cd doped in nickel ferrite samples were calculated using standard relation;

\[
a = d\sqrt{(h^2 + k^2 + l^2)} \text{ Å}...
\]

Where, \((a)\) is the lattice constant, \((d)\) is the interplanar spacing; \((h k l)\) is the miller indices. The obtained values of the lattice constant \((a)\) are shown in Figure 2. It can be seen from Figure 2 that the lattice constant increases with the substitution of cadmium in nickel ferrite and obeys Vegard’s law. This behavior of lattice constant with cadmium content \(x\) is explained on the basis of difference in ionic radii of Ni\(^{2+}\) and Cd\(^{2+}\). In the present series Ni\(_{1-x}\)Cd\(_x\)Fe\(_2\)O\(_4\), Ni\(^{2+}\) (0.72 Å) ions are replaced by larger Cd\(^{2+}\) (0.97 Å) ions; therefore, increase in lattice constant takes place. Our results are in good...
The variation of lattice constant as a function of Cd content x is shown in Figure 2. The unit cell volume (V) was calculated by using the following equation:

\[ V = a^3 Å^3 \]  \hspace{1cm} (2)

Where, V is the unit cell volume, ‘a’ is the lattice constant.

The unit cell volume (V) values show gradual increase with the increase of Cd content in the nickel ferrite system. The increase in cell volume is attributed to increase in lattice constant of the system under investigation.

The X-ray density (dx) was calculated by using the relation and values are shown in Figure 2:

\[ d_x = \frac{Z \times M}{V \times N_A} \] \hspace{1cm} (3)

Where, Z is the number of molecules per formula unit (Z = 8 for spinel system), M is molecular mass of the sample, V is the unit cell volume; NA is the Avogadro’s number.

Figure 2. lattice parameter ‘a’, density ‘d_x’, bulk density ‘d_B’, crystallite size (t), hopping length L_A and L_B of (A) and [B] site of Ni_{1-x}Cd_xFe_2O_4 (x = 0.0, 0.1, 0.2, 0.3, 0.4, and 0.5) nanoparticles.

It is observed from Figure 2 that X-ray density increases with increase in Cd content ‘x’. This behaviour of X-ray density is attributed to an increase in mass that overtakes the increase in volume of unit cell. The variation of X-ray density with Cd content x is shown in Figure 2 which increases with the increase in Cd content x. The bulk density of the present sample was obtained through Archimedes principle using toluene as an immersion liquid. The values of bulk density are reported in Figure 2. Bulk density (dB) of the investigated sample was measured using the Archimedes principle, its lower value i.e. (dB < dx) is attributed to the pore formation during synthesis processes. It can be understood from Figure 2 that the bulk density decreases with increase in cadmium substitution. The decrease in the density is correlated with decrease of atomic weight of substituted Cd^{2+} ions instead of Ni^{2+} ions. The atomic weights of Cd^{2+} and Ni^{2+} are 112.41 a.m.u. and 58.69 a.m.u., respectively. This decrease in density may also be a fact that Cd^{2+} is acting as slight accelerator of grain growth and favoring densification. This is evidence of accelerated densification during the sintering process which led to reduction of pore fraction. X-ray density and bulk density may be due the existence of pores in the samples, which depends upon the method of preparation, sintering temperature and sintering
conditions. The variation of bulk density as a function Cd content x is shown in Figure 2. The particle size of the Cd substituted nickel ferrite was calculated by using the most intense peak (311) and using the Debye-Scherer’s relation for small and uniform sized cubic crystals mentioned below.

\[ t = \frac{0.9 \lambda}{\beta \cos \theta} \]  

(4)

Where, \( \lambda \) is wavelength of the Cu-K\( \alpha \) radiation, \( \beta \) is the full width at half maximum, \( \theta \) is Bragg’s angle.

The obtained values of the crystallite size are shown in Figure 2. It is observed that particle size decreases with increasing Cd content x. The variation of crystallite size as a function Cd content x is shown in Figure 2.

The hopping length for tetrahedral A-site \( (L_A) \) and octahedral B-sites \( (L_B) \) are calculated using the values of lattice constant. The variation of hopping lengths in octahedral site \( [B] \) and tetrahedral \( (A) \) site with Cd content x is shown in Figure 2. It is observed from Figure 2 that the distance between the magnetic ions (hopping length) increases as Cd content x increases. This behavior of hopping length with x is analogous with behavior of ‘a’ with x, and may be attributed to the deference in the ionic radii of the constituent ions. Using the experimental values of lattice constant ‘a’ and oxygen positional parameter ‘u’ and substituting it into equations discussed elsewhere; the tetrahedral and octahedral bond length \( (d_{AX}, d_{BIX}) \), tetrahedral edge, shared and unshared octahedral edge \( (d_{AXE}, d_{BXE}, d_{BXEU}) \) were calculated and the values are shown Figure 4. It is observed that the tetrahedral bond length \( d_{AX} \) and octahedral bond length \( d_{BIX} \) increases as Cd content x increases. Figure 4, shows that the tetrahedral edge \( d_{AXE} \) increases and unshared octahedral edge \( d_{BXEU} \) does not vary much with composition while shared octahedral edge \( d_{BXE} \) increases. This could be related to the larger ionic radii of Cd as compared to Ni ions.

3.2. Scanning electron microscopy (SEM)

Surface morphology and average grain size of Cd\( \text{II} \) substituted Ni\( _{1-x} \)Cd\( _x \)Fe\( _2 \)O\( _4 \) nanoparticles were determined by using scanning electron microscope technique by selecting 35,000 magnification ranges. SEM images for the typical samples x = 0.0 and 0.1 are shown in Figure 3.

Figure 3. XRD Scanning electron microscope (SEM) image of typical sample for Ni\( _{1-x} \)Cd\( _x \)Fe\( _2 \)O\( _4 \) (x = 0.0 and 0.1) nanoparticles.

The SEM micrograph shows the grain growth is uniform and porous and uniform microstructure with spherical morphology of the ferrite samples. The uniform microstructure also indicates single-phase formation of the material. The agglomeration of these very fine nanoparticles into large clusters is also seen, as expected, because it is the usual tendency of magnetic nanoparticles. This is mainly due to the slow growth of particles in the adopted sol-gel auto combustion route of synthesis of magnetic nanoparticles. Furthermore, the agglomeration of particles is attributed to the interaction between magnetic particles. The effect of Cd substitution on the microstructure of NiFe\( _2 \)O\( _4 \) can be explained in terms of the increase pore mobility due to the creation of excess cation vacancies. Excess cation vacancy formation by doping the ferrite with high-valence cations can be argued from the site and
charge neutrality as well as the oxidation-reduction equilibrium of iron, which then promotes grain growth in NiFe₂O₄. The grain size of the typical samples Ni₁₋ₓCdₓFe₂O₄ (x = 0.0 and 0.1) were estimated by counting a sufficiently large number of grains to ensure accuracy. Average grain sizes are found to be in the nano regime for x = 0.0 (102 nm) and for x = 0.1 (80 nm).

3.3. Energy dispersive X-ray analysis (EDAX)

The EDAX measurement was done in order to determine the chemical composition on the surface of the sample to support our observations on the structure of the ferrite. The typical EDAX pattern of Ni₁₋ₓCdₓFe₂O₄ (x = 0.0 and 0.1) are shown in Figure 4. The results of energy dispersive X-ray analysis spectroscopy are in good agreement with its nominal composition. The EDAX plot gives the evidence of presence of Ni²⁺, Cd²⁺, Fe³⁺, and O²⁻ ions with proper ratio confirming the desired stoichiometric composition. Figure 4. gives elemental percentage for Ni₁₋ₓCdₓFe₂O₄ system. It is evident from Figure 4. that the elemental Ni²⁺, Cd²⁺, Fe³⁺ and O²⁻ ion are found to be in stoichiometric desired proportions. The EDAX quantification can be influenced by the surface crystalline defects of nanoparticles. This can also be taken into account to explain the difference between the values of the atomic ratio as determined by the EDAX and the expected value.

3.4. Infrared spectroscopy (IR)

The FTIR pattern of Ni₁₋ₓCdₓFe₂O₄ (x = 0.0, 0.1, 0.2, 0.3, 0.4, and 0.5) nanoparticles.
The IR spectra of the Ni$_{1-x}$Cd$_x$Fe$_2$O$_4$ (0.0$\leq x \leq$0.6) samples are shown in Figure 4, indicating the two absorption bands in the wave-number range of 350–800 cm$^{-1}$. These spectra are used to locate the band positions. It has been reported that the occurrence of $\nu_1$ (600 cm$^{-1}$) and $\nu_2$ (400 cm$^{-1}$) bands are attributed to the intrinsic vibrations of tetrahedral and octahedral groups, respectively. According to Waldron’s classification, the vibrations of the unit cell of cubic spinel can be constructed in the tetrahedral (A) site and octahedral [B] site. So, the absorption band $\nu_1$ is caused by the stretching vibration of the tetrahedral metal-oxygen bond, and the absorption band $\nu_2$ is caused by the metal-oxygen vibrations in octahedral sites. Further, these bands are mainly dependent on the Fe–O distances and the nature of the cations involved. The values of vibrational frequency band position are shown in Figure 4.

4. Conclusions

Cd$^{2+}$ substituted nickel ferrites, with nominal compositions Ni$_{1-x}$Cd$_x$Fe$_2$O$_4$ (0.0 $\leq x \leq$ 0.6) nanoparticles were successfully synthesized by a sol-gel auto combustion method. XRD results confirms the prepared samples are in the nanosize having a cubic spinel structure with single phase from $x = 0.0$ to $x = 0.5$ mol, whereas for higher substitution of Cd$^{2+}$ ion ($x \geq 0.5$) secondary phase of Fe$_3$O$_4$ has been observed. The lattice constant is found to increase with increasing Cd$^{2+}$ concentration $x$. The particle size of the samples calculated using the Debye Scherrer’s formula was obtained in the range of 27-16 nm. The average grain size obtained from scanning electron microscopy was found in the range of 102-80 nm. Energy dispersive spectroscopy analysis confirmed that the synthesized samples were near stoichiometric. Infrared spectra exhibit two distinct absorption bands near about 400 cm$^{-1}$ and 600 cm$^{-1}$ at octahedral and tetrahedral sites, respectively indicating the characteristic features of spinel ferrites.

5. References

[1] P.B. Kharat, J.S. Kounsalye, M.V. Shisode, K.J.J.o.S. Jadhav, N. Magnetism, Preparation and thermophysical investigations of CoFe 2 O 4-based nanofluid: a potential heat transfer agent, 32 (2019) 341-351.
[2] J.S. Kounsalye, P.B. Kharat, A.R. Chavan, A.V. Humbe, R. Borade, K. Jadhav, Symmetry transition via tetravalent impurity and investigations on magnetic properties of Li0. 5Fe2. 5O4, AIP Conference Proceedings, AIP Publishing LLC, 2018, pp. 050067.
[3] J.S. Kounsalye, P.B. Kharat, D.N. Bhoyar, K.J.J.o.M.S.M.i.E. Jadhav, Radiation-induced modifications in structural, electrical and dielectric properties of Ti 4+ ions substituted Li 0.5 Fe 2.5 O 4 nanoparticles, 29 (2018) 8601-8609.
[4] S.B. Somvanshi, S.A. Jadhav, M.V. Khedkar, P.B. Kharat, S. More, K.J.C.I. Jadhav, Structural, thermal, spectral, optical and surface analysis of rare earth metal ion (Gd3+) doped mixed Zn–Mg nano-spinel ferrites, DOI (2020).
[5] A.V. Humbe, P.B. Kharat, A.C. Nawle, K.J.J.o.M.S.M.i.E. Jadhav, Nanocrystalline Ni 0.70− x Cu x Zn 0.30 Fe 2 O 4 with 0$\leq x \leq$ 0.25 prepared by nitrate-citrate route: structure, morphology and electrical investigations, 29 (2018) 3467-3481.
[6] P.B. Kharat, A.V. Humbe, J.S. Kounsalye, K.J.J.o.S. Jadhav, N. Magnetism, Thermophysical investigations of ultrasonically assisted magnetic nanofluids for heat transfer, 32 (2019) 1307-1317.
[7] M. Shisode, P.B. Kharat, D.N. Bhoyar, V. Vinayak, M. Babrekar, K. Jadhav, Structural and multiferroic properties of Ba2+ doped BiFeO3 nanoparticles synthesized via sol-gel method, AIP Conference Proceedings, AIP Publishing LLC, 2018, pp. 030276.
[8] S.B. Somvanshi, S.R. Patade, D.D. Andhare, S.A. Jadhav, M.V. Khedkar, P.B. Kharat, P.P. Khirade, K.J.J.o.A. Jadhav, Compounds, Hyperthermic evaluation of oleic acid coated nano-spinel magnesium ferrite: enhancement via hydrophobic-to-hydrophilic surface transformation, DOI (2020) 155422.
[9] S.R. Patade, D.D. Andhare, P.B. Kharat, A.V. Humbe, K.J.C.P.L. Jadhav, Impact of crystallites on enhancement of bandgap of Mn1-xZnxFe2O4 (1$\geq x \geq$ 0) nanospinels, 745 (2020) 137240.
[10] P.G. Undre, P.B. Kharat, R. Kathare, K.J.J.o.M.S.M.i.E. Jadhav, Ferromagnetism in Cu $^{2+}$ doped ZnO nanoparticles and their physical properties, 30 (2019) 4014-4025.

[11] P.B. Kharat, A.R. Chavan, A.V. Humbe, K.J.J.o.M.S.M.i.E. Jadhav, Evaluation of thermoacoustics parameters of CoFe $^2$ O $^4$-ethylene glycol nanofluid using ultrasonic velocity technique, 30 (2019) 1175-1186.

[12] M.V. Shisode, A.V. Humbe, P.B. Kharat, K.J.J.o.E.M. Jadhav, Influence of Ba $^2+$ on opto-electric properties of nanocrystalline BiFeO $^3$ 3 multiferroic, 48 (2019) 358-367.

[13] J.S. Kounsalye, P.B. Kharat, M.V. Shisode, K.J.J.o.M.S.M.i.E. Jadhav, Influence of Ti $^4+$ ion substitution on structural, electrical and dielectric properties of Li 0.5 Fe 2.5 O 4 nanoparticles, 28 (2017) 17254-17261.

[14] B. Devmunde, A. Raut, S. Birajdar, S. Shukla, D. Shengule, K.J.J.o.N. Jadhav, Structural, electrical, dielectric, and magnetic properties of Cd2, 2016 (2016).

[15] A. Thakur, P. Mathur, M.J.J.o.P. Singh, C.o. solids, Study of dielectric behaviour of Mn–Zn nano ferrites, 68 (2007) 378-381.

[16] Z. Yue, J. Zhou, L. Li, H. Zhang, Z.J.J.o.m. Gui, m. materials, Synthesis of nanocrystalline NiCuZn ferrite powders by sol–gel auto-combustion method, 208 (2000) 55-60.

[17] S.K. Nath, K.H. Maria, S. Noor, S. Sikder, S.M. Hoque, M.J.J.o.m. Hakim, m. materials, Magnetic ordering in Ni–Cd ferrite, 324 (2012) 2116-2120.

[18] K. Nejati, R.J.C.C.J. Zabihi, Preparation and magnetic properties of nano size nickel ferrite particles using hydrothermal method, 6 (2012) 23.

[19] K. Modi, M. Rangolia, M. Chhantbar, H.J.J.o.m.s. Joshi, Study of infrared spectroscopy and elastic properties of fine and coarse grained nickel–cadmium ferrites, 41 (2006) 7308-7318.

[20] B.P. Jacob, S. Thankachan, S. Xavier, E.J.P.S. Mohammed, Effect of Gd$^{3+}$ doping on the structural and magnetic properties of nanocrystalline Ni–Cd mixed ferrite, 84 (2011) 045702.

[21] A. Nikumbh, A. Nagawade, G. Gugale, M. Chaskar, P.J.J.o.m.s. Bakare, The formation, structural, electrical, magnetic and Mössbauer properties of ferrispinels, Cd $^{1−}$ x Ni $^x$ Fe 2 O 4, 37 (2002) 637-647.