Journal of Alloys and Compounds 638 (2015) 121-126



Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jalcom

Effect of Cetyl trimethylammonium bromide (CTAB) amount on phase constituents and magnetic properties of nano-sized NiFe₂O₄ powders synthesized by sol-gel auto-combustion method





S. Alamolhoda*, S.M. Mirkazemi, T. Shahjooyi, N. Benvidi

School of Metallurgy and Materials Engineering, Iran University of Science & Technology (IUST), Narmak, Tehran 13114-16846, Iran

ARTICLE INFO

Article history: Received 28 December 2014 Received in revised form 7 February 2015 Accepted 25 February 2015 Available online 12 March 2015

Keywords: Ceramics Sol-gel processes Microstructure Magnetic measurement SEM X-ray diffraction

ABSTRACT

In this research nano-sized NiFe₂O₄ powders were synthesized with and without Cetyl trimethylammonium bromide (CTAB) surfactant addition by sol-gel auto-combustion method. Phase constituents, microstructure and magnetic properties as a result of different CTAB addition amounts were evaluated by X-ray diffraction (XRD), Raman spectroscopy, field emission scanning electron microscope (FESEM) and vibration sample magnetometer (VSM) techniques. XRD results designated that the combustion product consists of NiFe₂O₄ as the main phase and some amount of α -Fe₂O₃ and FeNi₃ phases. Raman spectroscopy represents the formation of NiO phase in addition to the mentioned phases. CTAB addition affects the phase constituents and elimination of α -Fe₂O₃ residuals from the combustion product while facilitating the formation of FeNi₃ phase. Also its addition leads to powder refinement based on FESEM images. Mean crystallite sizes of the samples by calculated by Scherrer equation showed a decreasing trend from 46 to 27 nm with increasing the amount of CTAB. Magnetic measurements showed that saturation magnetization increased from 36.96 emu/g to 51.07 emu/g by CTAB addition as a result of increased FeNi₃ amount. The intrinsic coercivity values (_iH_c) of the samples are in the range of 164– 175 Oe.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

Nickel ferrite (NiFe₂O₄) is one of the most important materials in the inverse spinel family exhibiting ferromagnetic properties with high saturation magnetization, excellent chemical stability and mechanical hardness, electrical resistivity and low eddy current loss in alternating current applications [1–4]. Nano ferrites are potential candidates for various applications which include their usage in microwave control components such as circulators, isolators, and phase shifters [5]. Also they are applicable for gas and humidity sensing, drug-delivery technology, high density magnetic storage media, MRI contrast agents, color imaging, ferro-fluids, high frequency (~GHz) devices electric and electronic applications, water treatment, biomedical and biotechnology fields, magnetic refrigerators and catalysts applications [4–9].

Nickel ferrite nano particles have been prepared by several methods such as hydrothermal [10], co-precipitation [11], micro emulsion [12], ball milling [13], sol-gel [14] and sol-gel auto-combustion [15]. It should be mentioned that the preparation method

influences the composition and microstructural characteristics of the synthesized powders [2,16].

Sol-gel auto-combustion method is a unique combination of the ignition and the chemical gelation processes. This method has the advantages of simple preparation, cost-effectiveness and gentle chemistry route resulting in ultra-fine and homogeneous powder [9].

There are some reports representing that in the aqueous wet chemistry methods, presence of surfactants and their concentration influences the morphology and size of the synthesized nanoparticles of different materials (e.g. α -Fe₂O₃, Cu₂O, Au and SrFe₁₂O₁₉) [17–20].

Barati et al. reported that Cetyl trimethylammonium bromide (CTAB) addition resulted in formation of single phase nickel ferrite and reduction of its crystallite size using sol–gel auto-combustion method [21]. But they did not report the effect of the amount of CTAB surfactant on the microstructure and magnetic properties of NiFe₂O₄. It was reported that CTAB amount influence on saturation magnetization and coercivity values of strontium hexaferrite synthesized by co-precipitation method [22]. Up to our knowledge there is no report about the effect of CTAB amount on

^{*} Corresponding author. Tel.: +98 21 77240540x2885. *E-mail address: alamolhoda@iust.ac.ir* (S. Alamolhoda).

phase constituents and magnetic properties of nano-sized NiFe₂O₄ powder synthesized by sol-gel auto-combustion method.

In this research nickel ferrite nano sized powders have been synthesized by sol-gel auto-combustion method. The effect of CTAB amount on phase formation, microstructure and magnetic properties of nickel ferrite nano-sized powders has been studied.

2. Materials and methods

In order to synthesize nickel ferrite stoichiometric amounts of metal nitrates: 7.35 g Fe(NO₃)₃·9H₂O (99% Merck) and 2.56 g Ni(NO₃)₂·6H₂O (99% Merck) were dissolved into 50 ml distilled water to make an aqueous solution. The molar ratio of Ni/ Fe was fixed to 1/2. Then 5.25 g citric acid (C₆H₈O₇.99% Merck) was added to the above mixture as a chelating agent with a nitrate to citrate ratio of 1:1. The solution was heated at 60 °C on magnetic stirrer with a rotating speed of 300 rpm to form a clear and green sol with pH < 1. The pH of the solution was raised to 7 by ammonia solution addition. Then different amounts of Cetyl trimethylammonium bromide (CTAB) C₁₉H₄₂BrN (99% Merck) was added to the solution as a surfactant. The CTAB amount was calculated according to the weight of metal nitrates. The resulting sol was heated at constant temperature of 80 °C on magnetic stirrer to complete the formation of the gel precursor. Then the gel undergoes a self-ignition reaction to form a very fine brown foamy powder. The codes of the combustion products with different CTAB addition amounts are shown in Table 1.

The phase identification of the combustion products has been performed by Philips X'pert Pro X-ray diffractometer (XRD) using Cu K α radiation (λ = 0.1541 nm). The XRD patterns were submitted to a quantitative analysis by the Rietveld method using MAUD (material analysis using diffraction) software [23]. Raman spectroscopy was performed on a BRUKER model SENTERRA Raman spectrometer. The morphology and microstructure of the nano particles were studied by a field emission scanning electron microscope (FESEM) model (TESCAN). Magnetic properties have been taken out at room temperature at the maximum applied field of 14 kOe by vibrating sample magnetometer (VSM) model MDK.

3. Results and discussions

X-ray diffraction patterns of the combustion products for the samples synthesized with and without CTAB addition are represented in Fig. 1. XRD results represent that the combustion product of the sample C0 mainly consists of nickel ferrite coexisting with some residual α -Fe₂O₃ and small amounts of FeNi₃ phase. Other researchers also reported presence of FeNi₃ phase in the combustion products in the synthesis process of NiFe₂O₄ by sol–gel auto-

Table 1

Codes of the combustion products with different C	CTAB amounts
---	--------------

Sample code	C0	C1.5	C3	C6	C9
Wt.% of CTAB addition	0	1	2	4	6



Fig. 1. XRD patterns of the combustion products of the samples synthesized with and without CTAB addition. \Box : NiFe₂O₄, Δ : α -Fe₂O₃, \blacktriangle : FeNi₃, \blacksquare : NiO.

combustion route [24]. The reason of FeNi₃ formation is explained to be the existence of citric acid which consumes most of the oxygen surrounding the precursor at the combustion stage. Therefore Fe and Ni metal ions as a result of scarcity of oxygen form FeNi₃ phase [24].

With CTAB addition the identified phases in the XRD pattern consists of NiFe₂O₄ and FeNi₃. Although there is a report that surfactant addition causes formation of single phase NiFe₂O₄ [21], presence of FeNi₃ phase is observable in all of the XRD patterns shown in Fig. 1.

XRD patterns illustrate that with CTAB additions hematite peaks are disappeared. Since Fe/Ni ratio was set to be 2/1, and FeNi₃ phase with Fe/Ni ratio of 1/3 is observed in the sample, presence of the other compounds consisting of iron is expected. The most probable phase is maghemite (γ -Fe₂O₃) since peaks of γ -Fe₂O₃ phase also overlap with NiFe₂O₄ peaks in the XRD pattern. It was reported that the oxidation product of magnetite (Fe₃O₄) is maghemite; and hematite could be formed by heat treatment of maghemite at temperatures of 400–700 °C [25–27]. The oxidation state of hematite is higher than that of maghemite therefore scarcity of oxygen in the combustion atmosphere might be the reason for the formation of maghemite. Also in addition to citric acid, CTAB plays the role of fuel in the sol–gel auto-combustion method for its hydrocarbon chain [21]. F/O (fuel/oxygen) ratios of different samples are shown in Table 2. When the molar ratio of metal

Table 2F/O ratio of the synthesized samples.

Sample code	C0	C1.5	C3	C6	C9
F/O ratio	1.35	1.54	1.74	2.13	2.52



Fig. 2. XRD pattern of the sample CO and JCPDS cards of NiFe₂O₄ and NiO phases.



Fig. 3. Raman spectra of samples C0, C1.5, C3 and C9.



Fig. 4. Dependence of approximated weight percentages of different phases to CTAB amount calculated by MAUD software.



Fig. 5. FESEM images of the samples (a) C0 and (b) C3.

nitrates to citric acid is equal and no CTAB addition is used (sample C0), F/O ratio is calculated to be equal to 1.35. With CTAB addition the F/O ratio would be increased causing more shortage of oxygen in the combustion process. By F/O increment formation of maghemite would be facilitated as a result of more deficiency of oxygen.

It was observed that below the crystal size of 30 nm only maghemite would be produced while above this size only hematite could be obtained [28]. Reduction of mean particle size by CTAB addition is reported for the synthesis of nanostructured Cu₂O particles [18] by sol-gel auto-combustion method. Therefore in addition to reducing atmosphere, refinement of the synthesized Fe₂O₃ particles by CTAB addition may also assist maghemite formation.

Presence of some amount of NiO phase is also probable in the samples since the peaks of NiFe₂O₄ phase are overlapping with NiO peaks in the XRD pattern (Fig. 1). Fig. 2 demonstrates that the intensity of (222) reflection at 37.33° in the standard JCPDS

86-2267 for NiFe₂O₄ phase is weak. While the intensity of (111) plane reflection at 37.44° is strong in the standard JCPDS 001-1239 for NiO phase. The observed peak in the XRD pattern of sample C0 is not as weak as the (222) reflection in the standard JCPDS 86-2267 card. So presence of some amount of NiO phase in the sample may be the reason for differences in peak intensities.

Fig. 3 shows the Raman spectra of the samples. It could be seen that there are Raman bands at about 212, 331, 482, 572 and a strong band at about 700 cm⁻¹ which respectively correspond to $F_{2g(1)}$, E_g , $F_{2g(2)}$, $F_{2g(3)}$ and A_g vibration modes for NiFe₂O₄ [29–32]. The shoulder like feature at lower wave number side of the Raman band at 700 cm⁻¹ is assigned to $A_{1g}(1)$ and $A_{1g}(2)$ modes reflecting the stretching vibration of Fe³⁺ and O²⁻ ions in tetrahedral site [30].

It was reported that NiO has Raman bands at 440, 560 and 740 cm⁻¹ [33]. The observed bands at 440 and 562 cm⁻¹ in the Raman spectra of the sample C0 can be attributed to the presence of NiO in this sample since the other bands of NiO have overlapped with the broad bands of NiFeO₄ at 700 cm⁻¹. Raman bands for maghemite are reported to be at 365, 500 and 700 cm⁻¹ [34,35]. The peaks at 500 and 700 cm⁻¹ are overlap with NiFe₂O₄ broad peaks. However there is a small peak at about 370 cm⁻¹ at the Raman spectra of the sample C9 which could be the Raman band of maghemite. As it was explained earlier, it is expected that with increasing F/O ratio the amount of maghemite phase increases.

Quantitative analyses performed by Rietveld method using MAUD software representing the dependence of weight percentage of different phases on CTAB amount are shown in Fig. 4. It should be noted that these quantities are not exact; particularly since γ -Fe₂O₃ peaks in the XRD pattern overlap with NiFe₂O₄ peaks; however they can represent relative phase changes by alternation in CTAB amount. It could be observed that with CTAB addition the amount of NiFe₂O₄ would increase above 25% and residual α -Fe₂O₃ amount could reduce about 20% at the same time. However as mentioned above, these changes may be as a result of formation of some γ -Fe₂O₃ phase in the sample.

Ouantitative analyses also show the presence of NiO phase in the samples. This enhances the probability of presence of NiO in the synthesized samples and it is in consistence with the above mentioned XRD standard cards in Fig. 2. The graph in Fig. 4d shows about 6-9% reduction in NiO amount by CTAB addition. The amount of NiO phase reaches to minimum in sample C3 and FeNi₃ phase amount reaches to a maximum in this sample (Fig. 4b and d). Fig. 4b shows that with CTAB addition FeNi₃ amount reaches to a maximum and then its amount would be decreased. F/O ratio is increased with surfactant addition and therefore it is expected to make the environment more reductive so FeNi₃ phase amount would be increased. After the increment there is a declining trend for FeNi₃ amount. This declining trend may be as a result of the higher exothermicity of the combustion process caused by surfactant addition [36]. The higher exothermicity of the combustion process may facilitate the interaction of the precursors by oxygen molecules present in the atmosphere. Therefore it is observed that NiO amount in the samples increases simultaneously with the decrease in FeNi₃ amount.

FESEM micrographs of the samples C0 and C3 (Fig. 5) represent morphology of NiFe₂O₄ nano sized particles and it seems that CTAB addition does not affect the particle morphology. The micrographs represent formation of smaller particles with a narrow size distribution with CTAB addition. Presence of CTAB influences the formation process of the particulate assemblies in the sol including nucleation, growth, coagulation and flocculation [37]. The basic role for surfactants in the synthesis of nanoparticles arises out of their ability for compartmentalization. This may reduce the reaction dimensionalities which could facilitate the nucleation process of the particulate assemblies. Also the reactants distribute themselves throughout the sol uniformly [38] which provides a narrow size distribution in the combustion product.

The complexes are assembled within the template of surfactant micelle in the sol [37] which restricts the amount of coagulation and therefore restricts the growth of particulate assemblies. The small particulate assemblies in the sol form smaller particles after combustion process.

Mean crystallite size of nickel ferrite in the samples with different CTAB amounts is calculated using XRD patterns and Scherrer's equation:

$$D = 0.9\lambda/\beta \cos \theta \tag{1}$$

where *D* is mean crystallite size, λ is the X-ray wavelength, β is the value of the full width at half maximum of the diffraction peaks, and θ is the diffraction angle at the peak maxima [39]. The results (Table 3) represent a decreasing trend in mean crystallite size by increasing CTAB amount for nickel ferrite particles.

Magnetization curves of the samples obtained from room temperature VSM measurement are shown in Fig. 6. M_{max} and $_{i}H_{c}$ quantities of the samples are listed in Table 4 and plotted in Fig. 7.

The reported M_s values for nanoparticles of NiFe₂O₄ are equal to 50.4 [16] and 46.53 emu/g [4] and the reported value for the bulk

 Table 3

 Calculated mean crystallite sizes of the samples with different CTAB amounts by Scherrer equation.

Sample code	Mean crystallite size (nm)
C0	46
C1.5	38
C3	33
C6	31
C9	27



Fig. 6. Magnetization curves of the samples.

Table 4

Magnetic properties of the combustion products of samples synthesized without and with different amounts of CTAB addition.

Sample code	M _{max} (emu/g)	_i H _c (Oe)	
C0	37	175.5	
C1.5	48.2	163.7	
C3	51	170.7	
C6	30.3	172	
C9	29.4	172	



Fig. 7. M_{max} and ${}_{i}H_{c}$ values for different samples.

sample is equal to 56 emu/g [40]. As it could be observed the obtained M_{max} value for sample C0 is 37 emu/g. Presence of antiferromagnetic α -Fe₂O₃ phase could be the reason of M_{max} value reduction [41]. By CTAB addition the M_{max} value increases from 37 to 51 emu/g; in sample C3, while with higher values of CTAB addition M_{max} values declines to 29.3 emu/g. The observed changes in M_{max} values may be as a result of the changes in phase constituents of different samples. FeNi₃ is a magnetic phase with saturation magnetization equal to 110 emu/g [42]. It could be observed that the trend of changes in FeNi₃ amount of different samples is in consistence with the trend of changes may be the main reason for reduction in M_{max} values.

4. Conclusions

Nano-sized NiFe₂O₄ powders were synthesized with and without CTAB addition by sol-gel auto-combustion method. Phase constituents of the combustion product were influenced by CTAB amount. By CTAB addition α -Fe₂O₃ peaks were disappeared and the amounts of FeNi₃ phase were changed by the variation of CTAB amount. FESEM results represent microstructure refinement and narrow sized distribution by CTAB addition. Also calculated mean crystallite sizes of the samples by Scherrer equation show a decreasing trend from 46 to 27 nm with increasing the amount of CTAB. Low amounts of CTAB addition (3 wt.%) increases the M_{max} value from 37 to 51 emu/g; while higher amounts of CTAB additions (6 wt.% and higher) reduces M_{max} values to about 30 emu/g which is related to different amounts of FeNi₃ phase in the samples.

Acknowledgements

The authors thank Dr S.M. Masoudpanah for providing some CIF files for calculations by MAUD software.

References

- T. Prabhakaran, J. Hemalatha, Combustion synthesis and characterization of highly crystalline single phase nickel ferrite nanoparticles, J. Alloys Comp. 509 (2011) 7071–7077.
- [2] M. Khairy, Synthesis, characterization, magnetic and electrical properties of polyaniline/NiFe₂O₄ nanocomposite, Synth. Met. 189 (2014) 34–41.
- [3] M. Salavati-Niasari, F. Davar, T. Mahmoudi, A simple route to synthesize nanocrystalline nickel ferrite (NiFe₂O₄) in the presence of octanoic acid as a surfactant, Polyhedron 28 (2009) 1455–1458.
- [4] P. Sivakumar, R. Ramesh, A. Ramanand, S. Ponnusamy, C. Muthamizhchelvan, Structural, thermal, dielectric and magnetic properties of NiFe₂O₄ nanoleaf, J. Alloys Comp. 537 (2012) 203–207.
- [5] A. Pradeep, P. Priyadharsini, G. Chandrasekaran, Production of single phase nano size NiFe₂O₄ particles using sol–gel auto combustion route by optimizing the preparation conditions, Mater. Chem. Phys. 112 (2008) 572–576.

- [6] P. Sivakumar, R. Ramesh, A. Ramanand, S. Ponnusamy, C. Muthamizhchelvan, Synthesis and characterization of nickel ferrite magnetic nanoparticles, Mater. Res. Bull. 46 (2011) 2208–2211.
- [7] S. Vivekanandhan, M. Venkateswarlu, D. Carnahan, M. Misra, A.K. Mohanty, N. Satyanarayana, Sol-gel mediated surface modification of nanocrystalline NiFe₂O₄ spinel powders with amorphous SiO₂, Ceram. Int. 39 (2013) 4105–4111.
- [8] P. Sivakumar, R. Ramesh, A. Ramanand, S. Ponnusamy, C. Muthamizhchelvan, Synthesis, studies and growth mechanism of ferromagnetic NiFe₂O₄ nanosheet, Appl. Surf. Sci. 258 (2012) 6648–6652.
- [9] P. Sivakumar, R. Ramesh, A. Ramanand, S. Ponnusamy, C. Muthamizhchelvan, A simple wet chemical route to synthesize ferromagnetic nickel ferrite nanoparticles in the presence of oleic acid as a surfactant, J. Mater. Sci.: Mater. Electron. 23 (2012) 1041–1044.
- [10] S. Komarneni, M.C. D'Arrigo, C. Leonelli, G.C. Pellacani, H. Katsuki, Microwavehydrothermal synthesis of nanophase ferrites, J. Am. Ceram. Soc. 81 (1998) 3041.
- [11] K. Maaz, S. Karim, A. Mumtaz, S.K. Hasanain, J. Liu, J.L. Duan, Synthesis and magnetic characterization of nickel ferrite nanoparticles prepared by coprecipitation route, J. Magn. Magn. Mater. 321 (2009) 1838–1842.
- [12] T. Hirai, J. Kobayyashi, I. Komasawa, Preparation of acicular ferrite fine particles using an emulsion liquid membrane system, Langmuir 15 (1999) 6291.
- [13] J.H. Liu, L. Wang, F.S. Li, Magnetic properties and Mössbauer studies of nanosized NiFe₂O₄ particles, J. Mater. Sci. 40 (2005) 2573–2575.
- [14] X. Liu, S. Fu, C. Huang, Magnetic properties of Ni ferrite nanocrystals dispersed in the silica matrix by sol-gel technique, J. Magn. Magn. Mater. 281 (2004) 234–239.
- [15] J. Azadmanjiri, S.A. Seyyed Ebrahimi, H.K. Salehani, Magnetic properties of nanosize NiFe₂O₄ particles synthesized by sol-gel auto combustion method, Ceram. Int. 33 (2007) 1623–1625.
- [16] P. Sivakumar, R. Ramesh, A. Ramanand, S. Ponnusamy, C. Muthamizhchelvan, Preparation and properties of nickel ferrite (NiFe₂O₄) nanoparticles via sol–gel auto-combustion method, Mater. Res. Bull. 46 (2011) 2204–2207.
- [17] Z. Pu, M. Cao, J. Yang, K. Huang, C. Hu, Controlled synthesis and growth mechanism of hematite nanorhombohedra, nanorods and nanocubes, Nanotechnology 17 (2006) 799–804.
- [18] H. Zhang, C. Shen, S. Chen, Z. Xu, F. Liu, J. Li, H. Gao, Morphologies and microstructures of nano-sized Cu₂O particles using a cetyltrimethylammonium template, Nanotechnology 16 (2005) 267–272.
- [19] S.K. Kang, S. Chah, C.Y. Yun, J. Yi, Aspect ratio controlled synthesis of gold nanorods, Korean J. Chem. Eng. 20 (2003) 1145–1148.
- [20] S.M. Mirkazemi, S. Alamolhoda, Z. Ghiami, Microstructure and magnetic properties of SrFe 12 O 19 nano-sized powders prepared by sol-gel autocombustion method with CTAB surfactant, J. Supercond. Novel Magn., doi: http://dx.doi.org/10.1007/s10948-014-2872-x (In press).
- [21] M.R. Barati, S.A. Seyyed Ebrahimi, A. Badiei, The role of surfactant in synthesis of magnetic nanocrystalline powder of NiFe₂O₄ by sol-gel auto-combustion method, J. Non-Cryst. Solids 354 (2008) 5184–5185.
- [22] D.Y. Chen, Y.Y. Meng, D.C. Zeng, Z.W. Liu, H.Y. Yu, X.C. Zhong, CTAB-assisted low-temperature synthesis of SrFe12019 ultrathin hexagonal platelets and its formation mechanism, Mater. Lett. 76 (2012) 84-86.
- [23] H.M. Rietveld, A profile refinement method for nuclear and magnetic structures, J. Appl. Cryst. 2 (1969) 65–71.
- [24] J. Zhu, D. Xiao, J. Li, X. Yang, Y. Wu, Characterization of FeNi3 alloy in Fe-Ni-O system synthesized by citric acid combustion method, Scr. Mater. 54 (2006) 109–113.
- [25] R.M. Cornell, U. Schwertmann, The Iron Oxides, second ed., Wiley-VCH Verlag GmbH & Co., Weinheim, 2003.
- [26] G. Schimanke, M. Martin, In situ XRD study of the phase transition of nanocrystalline maghemite (Γ-Fe₂O₃) to hematite (α-Fe₂O₃), Solid State Ionics 136–137 (2000) 1235–1240.
- [27] E. Darezereshki, One-step synthesis of hematite (α-Fe₂O₃) nano-particles by direct thermal-decomposition of maghemite, Mater. Lett. 65 (2011) 642–645.
- [28] R.F. Ziolo, E.P. Giannelis, B.A. Weinstein, M.P. O'Horo, B.N. Ganguly, V. Mehrotra, M.W. Russell, D.R. Huffman, Matrix-mediated synthesis of nanocrystalline γ-Fe₂O₃: a new optically transparent magnetic material, Science 257 (1992) 219–223.
- [29] Y. Shi, J. Dinga, Z.X. Shenb, W.X. Sun, L. Wa, Strong uni-directional anisotropy in disordered NiFe₂O₄, Solid State Commun. 115 (2000) 237–241.
- [30] D. Varshney, K. Verma, Substitutional effect on structural and dielectric properties of $Ni_{1-x}A_xFe_2O_4$ (A = Mg, Zn) mixed spinel ferrites, Mater. Chem. Phys. 140 (2013) 412–418.
- [31] S. Joshi, M. Kumar, S. Chhoker, G. Srivastava, M. Jewariya, V.N. Singh, Structural, magnetic, dielectric and optical properties of nickel ferrite nanoparticles synthesized by co-precipitation method, J. Mol. Struct. 1076 (2014) 55–62.
- [32] S. Liu, B. Xiao, L. Feng, S. Zhou, Zh. Chen, C. Liu, F. Chen, Z. Wu, N. Xu, W. Oh, Z. Meng, Graphene oxide enhances the Fenton-like photocatalytic activity of nickel ferrite for degradation of dyes under visible light irradiation, Carbon 64 (2013) 197–206.
- [33] R.E. Dietz, G.I. Parisot, A.E. Meixner, Infrared absorption and raman scattering by two-Magnon processes in NiO, Phys. Rev. B 4 (1971) 2302–2310.
- [34] Guilherme V.M. Jacintho, Paola Corio, Joel C. Rubim, Surface-enhanced Raman spectra of magnetic nanoparticles adsorbed on a silver electrode, J. Electroanal. Chem. 603 (2007) 27–34.

- [35] M.H. Sousa, J.C. Rubim, P.G. Sobrinho, F.A. Tourinho, Biocompatible magnetic fluid precursors based on aspartic and glutamic acid modified maghemite nanostructures, J. Magn. Magn. Mater. 225 (2001) 67–72.
- [36] I. Singh, R.K. Bedi, Surfactant-assisted synthesis, characterizations, and room temperature ammonia sensing mechanism of nanocrystalline CuO, Solid State Sci. 13 (2011) 2011–2018.
- [37] Y. Wang, C. Ma, X. Sun, H. Li, Preparation and characterization of SnO₂ nanoparticles with a surfactant-mediated method, Nanotechnology 13 (2002) 565–569.
- [38] S.G. Dixit, A.R. Mahadeshwar, S.K. Haram, Some aspects of the role of surfactants in the formation of nanoparticles, Colloids Surf. A 133 (1998) 69–75.
- [39] B.D. Cullity, Elements of X-ray Diffraction, second ed., Addison-Wesely Publishing Co., 1978.
- [40] M. George, A.M. John, S.S. Nair, P.A. Joy, M.R. Anantharaman, Finite size effects on the structural and magnetic properties of sol-gel synthesized NiFe₂O₄ powders, J. Magn. Magn. Mater. 302 (2006) 190–195.
- [41] C.S. Lin, C.C. Hwang, T.H. Huang, G.P. Wang, C.H. Peng, Fine powders of SrFe₁₂O₁₉ with SrTiO₃ additive prepared via a quasi-dry combustion synthesis route, Mater. Sci. Eng. B 139 (2007) 24–36.
- [42] Xuegang Lu, Gongying Liang, Yumei Zhang, Synthesis and characterization of magnetic FeNi₃ particles obtained by hydrazine reduction in aqueous solution, Mater. Sci. Eng. B 139 (2007) 124–127.