SYSTHESIS AND CHARACTERIZATION OF ALUMINIUM SUBSTITUTED NICKEL MAGNESIUM FERRITE NANOPARTICLES

LOW PEK KEE

A dissertation submitted in the fulfilment of the
requirements for the award of degree of
Master of Science

Faculty of Science
Universiti Teknologi Malaysia

MAY 2016

To my lovely parents and my helpful Professor

ACKNOWLEDGEMENT

Thanks to God for the accomplishment of this dissertation which seems impossible in the beginning. Special thanks to my supervisor, Prof. Dr. Zulkafli Othaman who was so helpful and offered good advices along the process of experiments and writing thesis. Sincere Appreciation to Dr. Ali A Ati, Samad Zare and Shadab Dabagh because of the emotional and technical supports when I was in need. Thanks to the laboratory officers at the Department of Physics and Ibnu Sina Institute of Fundamental Science Studies for their helps

ABSTRACT

With excellent magnetic and electrical properties, ferrite magnetic nanoparticles have wide range of applications in wide range of fields. With tuneable physical and chemical properties, ferrites can have more applications and become more suitable for advancing technology. Normally, two approaches are used in tuning the physical properties of ferrites, first approach is changing the synthesis methods and the second approach is altering the types of cations being introduced into the ferrites. In this study, Aluminium substituted nickel magnesium ferrite with general formula $Ni_{1-x}Mg_xFe_{2-x}Al_xO_4$ were synthesised with co-precipitation method. Three annealing temperature were chosen at 600°C, 800°C and 1000°C. The samples were characterised using X-ray diffractometer (XRD) and Fourier Transform Infrared Red Spectroscopy (FTIR) for structural analysis. Field emission scanning electron microscope (FESEM) was used to analyse the morphological property of the samples. Energy dispersive X-ray spectrometer was used to study the composition of the samples. The dielectric properties of the samples were analysed by using impedance analyser. XRD and FTIR shows the single phase spinel structure of the samples. Crystallite size decreases with increasing ratio of aluminium and magnesium except for the samples annealed at 600°C, and increases when the annealing temperature increases. Lattice constant of samples annealed at 800°C and 1000 °C are almost constant but becomes smaller when annealed at 600°C, which may due to redistribution of the cations with different annealing temperature. The degree of crystallinity increases as the annealing temperature increase, when the ratio of aluminium and magnesium reach 0.8, the degree of crystallinity deteriorated. FESEM micrograph shows the homogeneous distribution of the nanoparticles. Increment of dielectric constant and low loss factor of this substituted ferrites make it a good candidate for high frequency device applications.

ABSTRAK

Dengan sifat magnetik dan elektrik yang baik, nanopartikel ferit yang bermagnet mempunyai aplikasi yang banyak dalam bidang yang luas. Dengan sifat fizikal dan kimia yang boleh diubahsuai dengan mudah menjadikan nanopartikel ferit mempuyai aplikasi yang lebih banyak dan lebih sesuai digunakan dalam bidang teknologi yang semakin maju. Du acara yang biasa digunakan dalam mungubahsuai sifat-sifat fizikal ferit nanopartikel, iaitu mengguna cara sintesis yang berlainan atau mengubah kation yang berlainan dalam ferit. Dalam kajian ini, nikel magnesium ferit yang digantikan oleh aluminium dengan formula $Ni_{1-x}Mg_xFe_{2-x}Al_xO_4$ telah disintesis dengan menggunakan cara kimia dekoposisi dan disepuhlindap pada suhu 600 °C, 800 °C dan 1000 °C. Sampel yang sudah siap telah dicirikan dengan XRD dan FTIR untuk mengaji struktur sampel. FESEM telah digunakan dalam kajian morfologi sampel. EDX digunakan untuk mengkaji komposisi sampel. Sifat-sifat dielektrik telah dikaji oleh penganalisis impedan. Hasil XRD dan FTIR menunjukkan sampel mempunyai struktur spinel. Saiz kristal berkurang apabila nisbah magnesium dan aluminium meningkat dalam ferit ini kecuali sampel yang disintesis pada suhu 600°C, saiz kristal meningkat apabila suhu sepuhlintap meningkat. Pemalar kisi tidak berubah untuk sampel yang disintesis pada suhu 800°C dan 1000°C tetapi telah meningkat berbanding dengan sampel yang disintesis pada suhu 600°C, yang mungkin disebab oleh pengagihan semula kation pada suhu sepulindap yang berlainan. Darjah penghabluran meningkat apabila suhu anil untuk menyintesis sampel ini meningkat, apabila nisbah magnesium dan aluminium capai 0.8, tahap kristal telah jatuh. FESEM menunjukan taburan saiz nanopartikel adalah hampir sama. Peningkatan pemalar dielektrik dan keturunan faktor kehilangan menjadikan ferit yang mempunyai gantian sebagai calon yang sesuai untuk aplikasi frekuansi tinggi.

TABLES OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

EDX	Energy Dispersive X-Ray
FESEM	Field Emission Scanning Electron Microscope
FWHM	Full Width Half Maximum
FTIR	Fourier Transform Infrared Red
XRD	X-Ray Diffraction
AR	Analytical Grade

CHAPTER 1

INTRODUCTION

1.1 Background of study

Ferrites, a type of dielectric material and magnetic material are object of great interest recently due to wide range of applications including high density magnetic storage, contrast agents for magnetic resonance imaging (MRI), magnetic field assisted cancer treatment, ferrofluids, drug delivery (S.Rana *et al*., 2007), electronic devices such as inductors, transformers (Andris Sutka *et al*., 2015), gas sensing (Ghosh.P *et al*.,2015), and photocatalysts replacing titanium dioxide (TiO_2). (Kong Zi.Y *et al*., 2015).

Ferrites can be classified in three main types of crystalline structures, they are hexagonal ferrites with chemical formula $MFe_{12}O_{19}$, spinel ferrites with chemical formula MFe_2O_4 and garnet ferrites with chemical formula $M_3Fe_5O_{12}$ where M represents divalent ions. Different crystalline structure will have different properties hence different applications.

Spinel ferrites have been a subject of study due to their wide range of applications as shown above, with the high DC resistivity, low loss tangent and low eddy current loss, spinel ferrites are promising material for high frequency applications (Satish Verma *et al*., 2012a). They are also used to absorb the microwave. Radar absorbing paint used in painting stealth aircraft are made of ferrites (Gui.I.H and Maqsood.A, 2008a).

Spinel ferrites with general chemical formula MFe_2O_3, where M represents the divalent ions have crystal structure similar as naturally found Magnesium Aluminate ($MgAl_2O_4$). This crystal structure have cubic closed pack structure. This structure have two sites for cations to reside, which are tetrahedral site and octahedral site, normally referred as A sites and B sites. There are three types of spinel ferrites according to the distribution of the cations. When M^{2+} cations totally fill the tetrahedral sites and Fe^{3+} cations totally fill the octahedral sites, this crystal structure is called normal spinel structure. If the Fe^{3+} cations totally fill the tetrahedral sites and M^{2+} cations and Fe^{3+} cations both fill the octahedral sites, this crystal structure is called inverse spinel structure. Most ferrites spinel have both M^{2+} cations and Fe^{3+} cations fill both the tetrahedral sites and octahedral sites, this crystal structure is called mixed spinel structure. This structure have a parameter calls degree of inversion, normally symbolized by δ. For instance, zinc ferrite ($ZnFe_2O_4$) formed normal spinel structure. Nickel ferrite ($NiFe_2O_4$) and cobalt ferrite ($CoFe_2O_4$) formed inverse spinel structure, manganese ferrite ($MnFe_2O_4$) formed mixed spinel structure.

The net magnetization of the spinel ferrite are difference between magnetization of the A site and B site. Indeed, the magnetic moment of the ions in the A site and B site are arranged antiparallel with each other but still there is net magnetization due to unbalanced magnetic moment on the two sites, hence, spinel ferrites show ferrimagnetic properties. Substitution of other type of ions into the spinel ferrite may change the magnetic properties or electrical properties of the spinel ferrite because the original cations are forced to have new distribution among the A site and B site due to the new substitution (Raju.K *et al.*, 2013), for instance, introducing zinc or copper into nickel ferrite will obtain higher saturation magnetization (Rama Krishna.K *et al*., 2012). By introducing aluminium into cobalt ferrites will increase its' DC resistivity (Gui.I.H and Maqsood.A, 2008b)..

The magnetic and electrical properties depends on their shape and shape which in turn depends on their synthesis methods. Conventional ceramic method requires high temperature for the synthesis of the samples, and normally will obtain nanoparticles with poor stoichiometry and inhomogeneity. Wet chemical methods such as sol gel auto combustion method, co-precipitation method and hydrothermal method can produce better quality nanoparticles. Among the wet chemical methods, co-precipitation method have the advantages of low cost, high production rate, low temperature synthesis and produce nanoparticles with very small size (Binu P Jacob *et al*., 2011a).

Nickel ferrite process inverse spinel structure in which Fe^{3+} ions fill both the tetrahedral sites and octahedral sites, and Ni^{2+} ions only fill the octahedral sites. Owing to its' high magnetocrystalline anisotropy and high saturation magnetization, nickel ferrite has many technological applications such as repulsive suspension for levitated railway system, microwave absorber and so on (Nermin Kasapoglu *et al*., 2007). Magnesium ferrite have partially inverse spinel structure in which both the Fe^{3+} and Mg^{2+} ions fill both the tetrahedral and octahedral sites. Magnesium ferrite is a soft n-type semiconducting material. Magnesium ferrite has high magnetic permeability and high DC electrical resistivity and hence has many technological applications such as catalysts, colour imaging, sensors and so on (Bamzai.K.K *et al*., 2014a). Indeed, both the magnesium ferrite and nickel ferrite are applied in many electronic devices because of their high permeability at high frequency and also very high resistivity (Abdul Gaffoor *et al.*, 2014a)

Higher loss tangent materials are suitable for high frequency heating devices. Loss tangent represents the efficiency with which the electromagnetic wave energy is converted to heat. Meanwhile, with higher loss tangent, the microwave absorption will improve. H. Moradmard *et al* showed that introducing magnesium into nickel ferrite will increase their dielectric loss, decrease the dielectric constant, at the same time, the crystalline size of the magnesium increase first and then decrease then increase again (2015a). The crystalline size's result is consistent with Abdul Gaffoor *et al.* (2014b). The dielectric constant's result is consistent with John Berchmans.L *et al.* (2004a)

Addition of Al^{3+} ions into the ferrites change the ferrites' structural properties, dielectric properties, electrical properties in quite interesting manner. Satish Verma *et al*. showed there is a significant decrease in the particles' size after the Al^{3+} ions are introduced to the ferrite samples (2012b). Indeed, many research have shown that introduction of Al^{3+} ions into nickel ferrite have increase its resistivity and dielectric constant so this ferrite is very suitable to high applications which normally have low dielectric loss and eddy current loss (Maghsoudi.I *et al.*, 2013). .

In present study, aluminium substituted magnesium nickel ferrite ($Ni_{1-x}Mg_xFe_{2-x}Al_xO_4$) will be synthesized using co-precipitation method with x = 0.0, 0.2, 0.4, 0.6, 0.8 and 1.0, annealed at 600˚C, 800˚C and 1000 ˚C respectively. This study will allow us to understand the properties of this ferrite when both aluminium and magnesium is introduced to the nickel ferrite.

1.2 Problem Statement

Nickel ferrite ($NiFe_2O_4$) is a type of soft magnetic material with high saturation magnetization and high resistivity, making it a useful material for applications in transformers and high frequency telecommunications. Magnesium ferrite ($MgFe_2O_4$) is also a soft magnetic material showing n-type semiconducting behaviour. Magnesium-nickel ferrite show special dielectric, electrical, magnetic and structural properties. Addition of Al^{3+} ions into the ferrite can alter the structural, magnetic and also electrical properties of the ferrites.

Until recently, there are detailed studies on electrical, dielectric, structural and magnetic properties on Ni-Mg ferrite ($Mg_{1-x}Ni_xFe_{2-x}O_4$), but not any investigations about the structural, morphological and dielectric properties of the effects of annealing temperature on Ni-Mg ferrite. As far as we know there are no investigations about the effects of Al^{3+} ions' addition in to Ni-Mg ferrite. In this study, aluminium substituted nickel magnesium ferrite ($Ni_{1-x}Mg_xFe_{2-x}Al_xO_4$) with x = 0.0, 0.2, 0.4, 0.6 and 0.8 was synthesized and annealed at 600°C, 800°C and 1000°C.

Co-precipitation method was chosen due to its high production rate, low cost and better quality nanoparticles can be produced if compare to conventional ceramic method, hence suitable for large scale production. This study can be useful to study the change of properties of the samples due to different annealing temperature and also the change of properties due to aluminium substitution for appropriate applications.

1.3 Objectives of the Research

The objectives of this study are:

i. To synthesize ferrites aluminium substituted nickel magnesium ferrite with general formula $Ni_{1-x}Mg_xFe_{2-x}Al_xO_4$ using co-precipitation method with different annealing temperature.

ii. To determine the structural properties of aluminium substituted nickel magnesium ferrite ($Ni_{1-x}Mg_xFe_{2-x}Al_xO_4$) annealed at different temperature using X-ray diffractometer (XRD) and Fourier Transform Infra-Red spectroscopy (FTIR).

iii. To determine the morphological properties of aluminium substituted nickel magnesium ferrite ($Ni_{1-x}Mg_xFe_{2-x}Al_xO_4$) annealed at different temperature using Field Emission Scan Electron Microscopy (FESEM).

iv. To determine the dielectric properties (dielectric constant, loss factor (tan δ), dielectric loss) of aluminium substituted nickel magnesium ferrite ($Ni_{1-x}Mg_xFe_{2-x}Al_xO_4$) annealed at different temperature using impedance analyser.

1.4 Scope of Study

The scope of study is to synthesize the aluminium substituted nickel magnesium ferrite ($Ni_{1-x}Mg_xFe_{2-x}Al_xO_4$) with different annealing temperature (600°C, 800°C, 1000°C) using co-precipitation method and with Sodium Hydroxide (NaOH) as precipitating agent. After synthesis, the samples will be characterized by X-Ray Diffraction (XRD) and Fourier Transform Infra-Red Spectroscopy (FTIR) to study the structural properties of the samples. The structural and morphological properties of the samples will be characterized by using Field Emission Scanning Electron Microscope (FESEM). Finally, the dielectric properties of the samples such as dielectric constant, dielectric loss and loss factor (tan δ) will be characterized using impedance analyser.

1.5 Significant of Research

Ni-Mg ferrites show good properties and find many applications in technological field. The structural properties, morphological, electrical, dielectric, and magnetic properties of Ni-Mg ferrite was studied by some researchers, whereas continuing to check out and improve the quality of the ferrite is important for different applications.

Addition of Al^{3+} ions into the ferrites change the ferrites' structural properties, dielectric properties, electrical properties in quite interesting manner too. With different annealing temperature, the structural and morphological of the ferrite can be altered which in turn alter the magnetic and electrical properties of the prepared ferrite. So, in this study, by additional of Al^{3+} ions into Ni-Mg ferrites and also by altering the annealing temperature to prepare these samples can help us to find out the better quality ferrite to be utilized in industrial and technological field.

1.6 Thesis Outline

This thesis consists of five chapters, with the first chapter depict the problem statement, significant of study, objectives of research scope of study and background of study. The second chapter encompass the literature review of the necessary knowledge of this study including history of ferrite, normal structure of ferrite, applications of ferrite, basic concept of dielectric loss, dielectric constant and dielectric properties of ferrite, basic concept of magnetism and the magnetic properties of ferrite and also some background study of this research. In chapter three, all the preparation process and characterization process will be discussed. Chapter four will have all the results of the characterization and the discussions of the result. Finally, conclusions and some suggestions for future research can be found in chapter five.

REFERENCES

Abdul Gaffoor, Dachepalli Ravinder (2012), High-Temperature Thermoelectric Power Studies of Ni-Mg Ferrites, *World Journal of Condensed Matter Physics*, 2, 237-240, scientific research

Abdul Gaffoor, Ravinder.D (2014). Characterization of magnesium substituted nickel nano ferrites synthesized by citrate gel auto combustion method, *journal of engineering research and applications*, 4(4), 60-66, Department of Physics Osmania University Hyderabad.

Alex Goldman. Modern Ferrite Technology 2nd Edition (2006), Pittsburgh, PA, USA, Springer

Andris Sutka, Rainer Parna, Tanel Kaambre, Vambola Kisand (2015). Synthesis of p-type and n-type nickel ferrites and associated electrical properties, *phisica B: condensed matter*, 456, 232-236, Elsevier

Avadhesh Kumar Yadav, Rajneesh Kumar Singh, Prabhakar Singh (2016). Fabrication of Lanthanum Ferrite based Liquefied Petroleum Gas Sensor, *Sensors and actuators B: chemical*, 229, 25-30

Bamzai.K.K, Gurbinder Kour, Balwinder Kaur, Kulkarni.S.D (2014). Preparation, and Structural and Magnetic Properties of Ca Substituted Magnesium Ferrite with Composition $MgCa_xFe_{2-x}O_4$ (x = 0.00, 0.01, 0.03, 0.05, 0.07), *Journal of Materials*, 2014(184340), 8 pages, Hindawi Publishing Cooperation

Berchmans.L.J, Kalai Selvan.R, Selva Kumar.P.N, Augustin.C.O (2004). Structural and electrical properties of $Ni_{1-x}Mg_xFe_{2-x}O_4$ synthesized by citrate gel process, *journal of magnetism and magnetic materials*, 279, 103-110, Elsevier.

Bhosale.A.G, Chougule.B.K (2006). X-ray, infrared and magnetic studies of Al-substituted Ni ferrites, *materials chemistry and physics*, 97(2-3), 273-276, Elsevier

Cvejic.Z, Đurđić.E, Ivković Ivandekić.G, Bajac.B, Postolache.P, Mitoseriu.L, Srdić.V.V, Rakić.S (2015). The effect of annealing on microstructure and cation distribution of $NiFe_2O_4$, *journal of alloys and compounds*, 649(2015), 1231-1238, Elsevier

Daliya. S.Mathew, Ruey-Shin Juang (2007). An overview of the structure and magnetism of spinel ferrite nanoparticles and their synthesis in microemulsions, Chemical engineering journal, Vol 129, pg 51-65, Elsevier

Dumitrescu.A.M, Lisa.G, Lordan.A.R, Tudorache.F, Petrila.I, Borhan.A.I, Palamaru.M.N, Mihailescu.C, Leontie.L, Munteanu.C (2015). Ni ferrite highly organized as humidity sensors, *Materials chemistry and physics*, 156,170-179, Elsevier.

Eltabey.M.M, Massoud.A.M, Cosmin Radu (2014). Microstructure and Superparamagnetic Properties of Mg-Ni-Cd Ferrites Nanoparticles, *Journal of Nanomaterials*, 2014 (492832), 7 pages, Hindawi Publishing Corporation.

Gabal.M.A, Angari Y.M.Al, Zaki.H.M (2014), Structural, magnetic and electrical characterization of Mg–Ni nano-crystalline ferrites prepared through egg-white precursor, *journal of magnetism and magnetic materials*, 363(2014), Elsevier

Ghosh.P, Mukherjee.A, Fu.M, Chattopadhyay.S, Mitra.P (2015). Influence of particle size on H_2 and H_2S sensing characteristics of nanocrystalline nickel ferrite", *physics E*, 74, 570-575, Elsevier.

Goswami.A, Goswami Amit.P(1973). Dielectric and optical properties of ZnS films, Thin Solid Films, 16 (1973), 175-185, 1973, Elsevier Sequoia S.A.

Gui.I.H, Maqsood.A (2008). Structural,magnetic and electrical properties of cobalt ferrites prepared by sol-gel route, *Journal of alloys and compounds*, 465, 227-331, Elsevier

Ibrahim Sharifi, Shokrollahi.H, Amiri.S (2012). Ferrite-based magnetic nanofluids used in hyperthermia applications, *Journal of magnetism and magnetic materials*, 326(6), 903-915, Elsevier.

Imran Ahmad, Tahir Abbas, Ziya.A.B, Ghazanfar Abbas, Asghari Maqsood (2014). Size dependent structural and magnetic properties of Al substituted Co-Mg ferrites synthesized by the sol-gel auto combustion method, *Materials research bulletin*, 52, 11-14, Elsevier

Jacob Binu P, Ashok Kumar, Pant R P, Sukhvir Singh, Mohammed E M (2011). Influence of precipitation method on structural and magnetic properties of nickel ferrite nanoparticles, *Bull.Mater.Science*, 34(7), 1345-1350, Indian Academy of Sciences

JianZhen Hao, MingZhen Wei (2009). Characterization and magnetic properties of nanocrystalline nickel ferrite synthesized by hydrothermal method, *materials letters*, 63(13-14), 1183-1184, Elsevier

Kalyan Raju.M (2015). FT-IR studies of Cu substituted Ni-Zn ferrites for structural and vibrational investigations, *Chemical Science Transactions*, 4(1), 137-142, Elsevier

Kong Zi.Y, Wong Nyap.X , Lum Sim.W , Tan Sze.Y , Khan Maksudur R. , Cheng Chin.K (2015). The application of magnesium ferrite photocatalyst for photo treatment of methyl blue, *Journal of engineering science and technology*, SOMCHE 2014 & RSCE 2014 Conference, Jan 2015, School of Engineering, Taylor's University, issue 4, 1-10

Kumar.L, Pawan Kumar, Amarendra Narayan, Manoranjan Kar (2013). Rietveld analysis of XRD patterns of different sizes of nanocrystalline cobalt ferrite, *international nano letters*, 3(8), 12 pages, Elsevier.

Luciano Menini, Pereira.M.C, Parreira.L.A, Fabris.J.D, Gusevskaya.E.V (2008). Cobalt- and manganese-substituted ferrites as efficient single-site heterogeneous catalysts for aerobic oxidation of monoterpenic alkenes under solvent-free conditions, *Journal of catalysis*, 254(2), 355-364, Elsevier

Maaz.K , Karim.S, Mumtaz.A, Hasanain.S.K, Liu.J, Duan.J.L (2009). Synthesis and magnetic characterization of nickel ferrite nanoparticles prepared by co-precipitation method. *Journal of Magnetism and Magnetic Materials,* 321, 1838–1842

Maghsoudi.I, Shokrollahi.H, Hadianfard.M.J, Amighian.J (2013). Synthesis and characterization of $NiAl_xFe_{2-x}O_4$ magnetic spinel ferrites produced by conventional method, *Powder Technology*, 235, 110–114, Elsevier

Marinca.T.F, Chicinaş.I, Isnard.O, Pop.V, Popa.F (2011). Synthesis, structural and magnetic characterization of nanocrystalline nickel ferrite—$NiFe_2O_4$ obtained by reactive milling, *Journal of alloys and compounds*, 509(30), 7931-7936, 2011, Elsevier

Mitsuo Sugimoto (1999). The past, present and future of ferrites, journal of American Ceramic Society, 82(2), 269-280, Wiley.

Moradmard.H, Farjami Shayesteh.S, Tohidi.P, Abbas.Z, Khaleghi.M (2015). Structural, magnetic and dielectric properties of magnesium doped nickel ferrite nanoparticles, *journal of alloys and compounds*, 650(2015), 116-122, Elsevier

Mozaffari.M, Abooalizadeh.Z, Amighian.J (2011). Investigation of magnetic properties of Al substituted nickel ferrite nanopowders, synthesized by the sol–gel method, *journal of magnetism and magnetic materials*, 323(23), 2997-3000, Elsevier.

Mozaffari.M, Amighian.J(2003). Preparation of Al-substituted Ni ferrite powders via mechanochemical processing, *Journal of magnetism and magnetic material*, 260(1-2), 244-249, Elsevier

Nermin Kasapoglu, Abdulhadi Baykal, Muhammet S. Toprak *(2007).* Synthesis and Characterization of $NiFe_2O_4$ nano-octahedrons by EDTA-assisted hydrothermal method, *Turk J Chem*, 31, 659-666, Tubitak.

Olsen.E, Thonstad.J (1999). Nickel ferrite as inert anodes in aluminium electrolysis: Part I Material fabrication and preliminary testing, *Journal of applied electrochemistry*, 29(3), 293-299, Springer

Pradeep.A, Chandrasekaran.G (2006). FTIR study of Ni, Cu and Zn substituted nano-particles of $MgFe_2O_4$, materials *letters,* 60 (3), 371-374, Elsevier.

Ra´ul Valenzuela (2011). Novel Applications of Ferrites, review paper , Hindawi Publishing Corporation physics research international, 9 pages.

Rachid Amrousse, Toshiyuki Katsumi (2012). Substituted ferrite $M_xFe_{1-x}Fe_2O_4$ (M = Mn, Zn) catalysts for N_2O catalytic decomposition processes, *Catalysis communications*, 26, 194-198, Elsevier

Raghvendra Singh Yadav, Jaromir Havlica, Jiri Masilko, Lukas Kalina, Jaromir Wesserbauer, Miroslava Hajduchova, Vojtech Enev, Ivo Kuritka, Zuzana Kozakova (2015). Effects of annealing temperature variation on the evolution of structural and magnetic properties of $NiFe_2O_4$ nanoparticles synthesized by starch-assisted sol–gel auto-combustion method, *journal of magnetism and magnetic material*, 394, 437-447, Elsevier

Raju.K, Balaji.C.G, Venugopal Reddy.P (2013). Microwave properties of Al and Mn doped nickel ferrites at Ku band frequencies, *Journal of Magnetism and Magnetic Materials*, 354, 383-387, Elsevier

Rama Krishna.K, Ravinder.D, Vijaya Kumar.K , Abraham Lincon.Ch (2012). Synthesis, XRD & SEM Studies of Zinc Substitution in Nickel Ferrites by Citrate Gel Technique, *World journal of condensed matter physics*, 2,153-159, Scientific Research

Rana.S, Gana.A, Srivastava.R.S, Misra.R.D.K (2007). On the suitability of nanocrystalline ferrites as a magnetic carrier for drug delivery: Functionalization, conjugation and drug release kinetics, *actabiomaterialia*, 3(2), 233-242, Elsevier

Ravindar Tadi, ong-Il Kim, Anand Kumar Sarella, Cheol Gi Kim, Kwon-Sang Ryu (2010). Relation of structure and magnetic properties in nickel substituted $MgFe_2O_4$, *journal of magnetism and magnetic materials*, 322(21), 3372-3376, Elsevier.

Razia Nongjai, Khalid Mujasam Batoo, Shakeel Khan (2010). Study of Structural and Dielectric Properties of Ni-Mg Ferrite Nanoparticles, CP1313, *International conference on physics of emerging functional materials*, *22-24 Sept 2010, Mumbai, (India)*, American Institute of physics.

S. G. Bachhav, R. S. Patil, P. B. Ahirrao, A. M. Patil, and D. R. Patil, “Microstructure and magnetic studies of Mg-Ni-Zn-Cu ferrites,” *Materials Chemistry and Physics*, vol. 129, no. 3, pp. 1104–1109,2011

Satish Verma, Jagdish Chand, M. Singh (2012). Structural, magnetic and Mossbauer spectral studies of aluminium substituted Mg-Mn-Ni ferrites ($Mg_{0.2}Mn_{0.5}Ni_{0.3}Fe_{2-y}O_4$), *Journal of alloys and compounds*, 551, 715-721, Elsevier

Seema Joshi (2014). Structural, magnetic, dielectric and optical properties of nickel ferrite nanoparticles synthesized by co-precipitation method, *journal of molecular structure*, 1076(2014), 55-62, Elsevier

Shultz Michael.D, Calvin Scott, Fatouros Panos.P, Morrison Shannon.A, Carpenter Everett (2007). Enhanced ferrite nanoparticles as MRI contrast agents, Journal of magnetism and magnetic materials, 311(1), 464-468, Elsevier

Sophie Laurent, Silvio Dutz, Hafeli Urs.O, Morteza Mahmoudi (2011). Magnetic fluid hyperthermia: Focus on superparamagnetic iron oxide nanoparticles, *Advanced in colloid and interface science*, 166 (1-2), 8-23, Elsevier

Tulliani.M, Baroni.C, Lopez.C, Dessemond.L (2011). New NO*x* sensors based on hematite doped with alkaline and alkaline-earth elements, *Journal of European Ceramic Society*, 31(13), 2357-2364, Elsevier.

Vucinic-Vasic.M, Bozin.E.S, Bessais.L, Stojanovic.G, Kozmidis Lubiric.U, Abeykoon.M, Jancarll.B, Maden.A, Krememovic.A, Antic.B (2013). Thermal Evolution of Cation Distribution/Crystallite Size and Their Correlation with the Magnetic State of Yb-Substituted Zinc Ferrite Nanoparticles, *the journal of physical chemistry C*, 117, 12358−12365, ACS publications

Wahba.A.M, Aboulfotoh Ali.N, Eltabey.M.M (2014). Effect of Al-ion substitution on structural and magnetic properties of Co-Ni ferrites nanoparticles prepared via citrate precursor method, *material chemistry and physics*, 146(3), 224-229, Elsevier.

Zhigang Zhang, Yihan Liu, Guangchun Yao, Guoyin Zu, Xiao Zhang, Junfei Ma (2012). Solid state reaction synthesis of $NiFe_2O_4$ nanoparticles by optimizing the synthetic consitions, Physica E, 45(2012), 122-129, Elsevier.