Raman Spectroscopic and Electrochemical Measurements of Dynamic Shocked MnFe₂O₄ Nano-Crystalline Materials

A. Sivakumar

Abdul Kalam Research Center, Sacred Heart College

S.Sahaya Jude Dhas

Kings Engineering College

P. Sivaprakash

Bharathidasan University

Abdulrahman I. Almansour

King Saud University

Raju Suresh Kumar

King Saud University

Natarajan Arumugam

King Saud University

Karthikeyan Perumal

The Ohio State University

S. Arumugam

Kings Engineering College

Martin Britto Dhas (✉ martinbritto@shcpt.edu)

Sacred Heart College <https://orcid.org/0000-0003-0896-7534>

Research Article

Keywords: Shock waves, MnFe₂O₄, Raman spectroscopy, electrical conductivity, lattice disorder

Posted Date: July 30th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-759475/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Version of Record: A version of this preprint was published at Journal of Inorganic and Organometallic Polymers and Materials on September 25th, 2021. See the published version at

Abstract

Divalent ferrite nano-crystalline materials subjected to shock wave recovery analysis have received non-debatable attention among the materials scientists due to their outstanding contribution that has fueled the enrichment of high-pressure ferrites science which act as the focal-point of the current research theme. On those lines, we intend to provide the Raman spectroscopic and electrochemical measurements of manganese ferrite nanoparticles (MnFe_2O_4 NPs) at dynamic shocked conditions. Raman spectroscopic analysis has revealed the stability of the tetrahedral (A-site) and octahedral (B-sites) sites of Mn^{2+} ions as well as Fe^{3+} ions at shocked conditions. Cyclic-voltammetry (CV-analysis) and impedance spectroscopic measurements of shocked samples have demonstrated the electro-chemical properties of MnFe_2O_4 NPs whose electrical conductivity is found to be reduced while increasing the number of shock pulses. The consolidated results provide the solid evidence that the test sample's crystal structure does not undergo any crystallographic phase transitions or mixed spinel states at shocked conditions.

Introduction

The investigation of knock-on effects influenced by shock waves on materials could make inroads wherein the emerging advancements are looming larger with ever increasing horizons of cutting edge technology, so much so that impending rapid progress is on the cards. On those lines, comprehending the crystallographic and magnetic phase stability of the ferrite nano-materials at high-pressure and high-temperature environments is one of the important hotspot research topics to draw the convincing results of the structural stability of the materials as well as to find new materials of crystallographic configuration with novel functional properties. According to the literature, the majority of the divalent ferrite NPs such as CuFe_2O_4 , CoFe_2O_4 , NiFe_2O_4 , ZnFe_2O_4 , MnFe_2O_4 , MgFe_2O_4 and BaFe_2O_4 have been analyzed by X-ray diffraction and Raman spectroscopic techniques at high-pressure conditions and several interesting results have been accounted so far [1–10]. On the one hand, the crystallographic features due to the effect of pressure compression on ferrite NPs have been quite well known while on the other hand, the effect of pressure compression impacted on the ferrite materials' functional properties such as optical transmittance, dielectric constant, capacitance and electrical conductivity are relatively unknown as compared to the crystallographic details. The remarkable response of nanoparticles on their physical and chemical properties to the external stimuli of high pressure, temperature, gamma rays, and shock waves is quite well known [11–15].

As an integral part of the high-pressure research in the global scenario, dynamic shock waves also have a prominent role in the research of materials science which can create a progressive way forward to understand the stability of materials and provide the scope of tuning the properties of materials including the crystallographic structures which have been well documented to a certain extend in the last couple of decades. Moreover, the materials investigated are both bulk and nano-sized which really emphasize the intuitive ideas such that these materials could be exploited for multiple of applications [16–20]. On the

one hand, in the case of metal oxide nano materials, several interesting crystallographic and magnetic phase transitions have been observed in a variety of materials such as TiO_2 , ZrO_2 and Co_3O_4 [21–23]. On the other hand, in the case of divalent ferrite NPs such as ZnFe_2O_4 , NiFe_2O_4 and MnFe_2O_4 , stable crystallographic and magnetic phases have been witnessed at shocked conditions which have also thrown a few more fascinating results [24–26]. Interestingly, ZnFe_2O_4 NPs exhibit paramagnetic to superparamagnetic switchable magnetic phase transitions in accordance with the counts of shock pulses of 0, 50, 100 and 150 [24]. NiFe_2O_4 and MnFe_2O_4 NPs have stable crystallographic and magnetic states at shocked conditions [25, 26]. But there is no report available so far on Raman spectral and electrochemical properties for NiFe_2O_4 and MnFe_2O_4 NPs at shocked conditions. In order to have access to the fabrication of electronic devices, knowing the electronic transport properties and their stabilities of materials are highly required since there are lots of changes that can occur in the transport properties as and when sudden environmental changes happen [27, 28]. Moreover, at shocked conditions, there have been remarkable changes observed for a few structurally stable materials [29, 30]. Hence, we intend to investigate the electrical transport properties of technologically important MnFe_2O_4 NPs at shocked conditions which could make a probable justification on the stability of crystal structure and the associated material properties contributing to their performances at shocked conditions. Hence, herein as the continuation of our previous report, we account the Raman spectroscopic and electrical transport properties of MnFe_2O_4 NPs at shocked conditions. The title material deserves several technologically important applications such as site-specific drug delivery, magnetic-storage devices, sensors, energy storage applications, magnetic resonance imaging and photo-magnetic materials, RADAR and high-speed data transfer communication systems [31–33]. MnFe_2O_4 NPs crystallize with the cubic normal spinel space group at ambient temperature (Mn^{2+} occurred only in tetrahedral site (A-site) of MnFe_2O_4) and also it can crystallize with the inverse spinel as well as mixed spinel cubic phase while changing the synthesis process (For inverse spinel, Mn^{2+} occurred only in octahedral site (B-site) of MnFe_2O_4) and in the case of mixed spinel, Mn^{2+} ions are present both in the tetrahedral and octahedral sites [32, 33]. Interestingly, the transition from the normal spinel to the mixed spinel of ZnFe_2O_4 NPs has been observed at shock wave loaded conditions and the corresponding Raman spectroscopic results have been communicated elsewhere. Hematite (Fe_2O_3 NPs) also show significant enhancement of electrical conductivity at shocked conditions while being in the same crystallographic phase [35, 36]. In the case of MnFe_2O_4 , possibilities of such kind of changes are on the higher scale at shocked conditions since both the ferrites belong to the ZnFe_2O_4 type normal spinel category at room temperature. Herein, we account the details of the Raman and electrochemical properties of the control and shocked MnFe_2O_4 NPs.

Experimental Section

The synthesis process of MnFe_2O_4 NPs and the procedure of shock wave loading have been presented in the previous paper and provided as a supplementary data in supplementary section [26]. The electrochemical measurements have been carried out by utilizing an electrochemical workstation (SP-150, BioLogic Science Instruments, France) at ambient temperature. In order to perform electrochemical

analysis, the required electrode has been made by blending 80 wt% of the obtained active material (MnFe_2O_4), 10 wt % of the conductive carbon black and 10 wt% of polyvinylidene fluoride (PVDF) binder along with the solution of 0.3 mL N-methylproline (NMP). The obtained uniform slurry has been painted on the well-cleaned nickel foam ($1\text{ cm} \times 1\text{ cm}$) which has been kept to air dry for 24 hours at ambient conditions. For the preparation of the electrode, the required mass of the active material (1 mg) has been measured by a digital weighing device. The electrochemical measurements have been performed making use of a three-electrode cell possessing 3 mol electrolyte solution of KOH such that the combination of these have been made use of as the working electrodes wherein Pt wire and Ag/AgCl in the saturated KCl have been chosen as the counter and as the reference electrode, respectively. Shock wave loaded sample electrodes of counts 50,100 and 150 have been prepared. The cyclic analysis of voltammetry (CV) has been performed for various applied potential ranging from 0 V to 0.5 V. Followed by the cyclic voltammetry, electrochemical impedance spectroscopic (EIS) analysis has been accomplished for the frequency ranging between 0.01 Hz and 1 kHz while the amplitude of 5 mV has been maintained as the open circuit potential.

Results And Discussion

Raman Spectroscopy

Raman spectroscopy is one of the prime tools being used to investigate the crystallographic phase details, lattice disorder, charge and spin-lattice coupling and local cation distributions [32]. Especially in ferrite materials, the transport properties are partially dependent on the cation distributions in the tetrahedral (A-site) and octahedral (B-site) sites. Hence, the Raman spectroscopic analysis (LabRAM HR Evolution, France) has been carried out for the samples of both the control and shocked. The obtained profiles of the Raman spectra are presented in Fig. 1.

According to the factor group analysis, cubic MnFe_2O_4 spinel has five Raman active modes as that of A_{1g} , E_g and $3F_{2g}$. Among the Raman active modes, A_{1g} and $3F_{2g}$ Raman modes belong to the tetrahedral (A-site) and E_g Raman mode belongs to the octahedral (B-site). As seen in Fig. 1, the control sample has four Raman modes such as A_{1g} , $F_{2g}(2)$, E_g and $F_{2g}(1)$ whose corresponding Raman positions are 650, 407, 293, and 221 cm^{-1} , respectively and the observed Raman bands are well-matched with the previous reports of the normal spinel MnFe_2O_4 NPs [32]. No considerable change is obtained under shock loading which is clearly evident for the mere naked eye.

But, while seeing the zoomed versions of the tetrahedral and the octahedral sites, slight changes are observed in terms of the ratio of Raman intensity that is between the tetrahedral and the octahedral sites in accordance with the number of shock pulses. As reflected in Fig. 2, the peak of $F_{2g}(1)$ for the control MnFe_2O_4 NPs has maximum intensity than that of the other Raman peaks such as E_g and $F_{2g}(2)$ which remain the same for all the other shocked conditions. But, E_g Raman band intensity increases slightly on increasing the number of shock pulses whereas $F_{2g}(1)$ Raman intensity reduces on increasing the

number of shock pulses. Moreover, the above-mentioned Raman bands have undergone a shift towards the lower frequency corresponding to the counts of shock pulses and the respective Raman shifts are depicted in Fig. 3.

The observed changes both in Raman band intensity and Raman shifts in accordance with the number of shock counts could have lead to lattice defects along with the redistribution of divalent and trivalent cations in the A and B sites wherein the interaction between oxygen and cations in the octahedral as well as the tetrahedral positions are strongly affected [36]. In the normal spinel structure, the divalent ions (Mn^{2+} in MnFe_2O_4) occupy the A site only whereas the trivalent ions (Fe^{3+} in MnFe_2O_4) occupy the B sites only. Considering the structure of inverse spinel, half of the B sites are occupied by the divalent ions while the rest of the B sites are occupied by the trivalent ions in addition to the occupancy of the entire A sites [32]. At high-pressure and high-temperature conditions, the migration of Mn^{2+} ions from the A to the B sites can occur. Theoretically, this would mean an effective increase in unit cell volume with which a significant XRD peak shift would have occurred for the higher inversion degree for MnFe_2O_4 [37]. Even a minor number of Mn^{2+} changes to Mn^{3+} ions in the B-sites, it significantly affects the XRD peak positions [26]. But, such changes have not been observed in the XRD peak positions at shocked conditions. Hence, it is confirmed that there is no inverse spinel structure that has been formed at shocked conditions. Therefore, the observed changes in the Raman band intensity may be due to the local lattice distortions. But, the cubic normal spinel phase of MnFe_2O_4 remains the same even after 150 shocked conditions which are well corroborated with the previously reported XRD results [26]. It could be noted that, at shocked conditions, the technologically important materials such as TiO_2 and Co_3O_4 NPs undergo significant Raman shifts due to the occurrence of the crystallographic phase transitions [21, 23].

Cyclic-voltametry Analysis

The Cyclic-voltammetric study has been performed to analyze the specific capacitance of the title material at shocked conditions which are presented in Fig. 4. The variation of the electrochemical performance of the control and shocked samples have been analyzed with different scan rates such as 5, 10, 20, 50, and 100 mV s^{-1} in the potential range of 0 – 1.0 V. As seen in Fig. 4, while increasing the scan rate, the positive shifts are observed in the redox peaks with respect to the anodic and cathodic potentials as well as the increased loop area with respect to the scan rate which is the usual behavior found in materials of ideal capacitive behavior [38].

It could be noted that the CV loop shapes and the loop widths of the control and shocked samples are almost similar while at different rates of shocked conditions. From an initial viewpoint, it could be seen that there is no significant change that has been observed in the capacitance value at shocked conditions. Furthermore, we have calculated the specific capacitance of both the control and shocked MnFe_2O_4 NPs using the standard formulation and the obtained values of specific capacitance in accordance with the scan rates are portrayed in Fig. 5. As seen in Fig. 5, the values of specific capacitance are reduced while increasing the scan rate for all the samples. Even at a lower scan rate, the

electrolyte ions have adequate time to penetrate the pores of the electrode material because of their higher value of specific capacitance.

For better understanding the shapes of CV loops and the values of specific capacitance with respect to the number of shock pulses, the comparison loops are presented in Fig. 6a. All the loops are similar in their shape for the samples such that no change is observed in their respective values of potential with respect to the number of shock pulses and the corresponding values of specific capacitance with respect to the number of shock pulses are plotted as presented in Fig. 6b. Hence, it is clear that no cationic re-distributions appear at shocked conditions and the observed slight changes may be due to the lattice defects and surface changes of the particles. It could be noted that the observed values of specific capacitance with respect to the number of shock pulses have not changed significantly.

Electrochemical Impedance Spectroscopic Analysis

Furthermore, we have performed the electrochemical impedance spectroscopic analysis to understand the behavior of electrical resistance under shock loading. Note that the variation of the microstructure, lattice disorder and cation redistribution can influence changes in the electronic transport properties in such a way that several high-pressure compression experiments have been performed on this theme providing several interesting results [11]. Hence, electrochemical impedance spectroscopic analysis (EIS) has been performed and the obtained Cole-Cole plots of the control and shocked samples are portrayed in Fig. 7. As per the normal spinel crystal structure of MnFe_2O_4 NPs, the interactions of the Mg^{2+} ion in the tetrahedral sites and Fe^{3+} ions in the octahedral sites are quite low hence it has lower electrical conductivity. As seen in Fig. 8, the control sample gives rise to an in-complete semi-circular arc and shocked samples also show a similar trend of semi-circular arcs with slight changes. Especially in the grain resistance portion (higher frequency region), the width of the first semi-circular arc is increased with respect to the number of shock pulses and the observed zoomed version of the Cole-Cole plots are depicted in Fig. 8. As the semi-circular arc width increases, the electrical resistance also increases. Hence, it is clear that the impact of applied shock waves has increased the values of electrical resistance (bulk grain resistance) with respect to the number of shock pulses which may be due to the formation of lattice defects in the cubic spinel, grain boundary region that has been disordered resulting in a tremendous increase in electron scattering [35, 38]. The mobility of charge carriers have a high dependency on temperature and pressure such that the reduction in mobility could have enforced a reduction in the electrical conductivity due to the change occurring in activation energy. Similar results of slight changes in the values of saturation magnetization have been witnessed in accordance with the counts of shock pulses [26].

Conclusion

Drawing the summary of the present experimental results, Raman spectroscopic and electro-chemical properties have been investigated for the control and shocked samples. Raman spectroscopic results

provide a clear justification on the crystallographic phase stability of the cubic normal spinel lattice of MnFe_2O_4 NPs at shocked conditions which is well corroborated with the previously reported X-ray diffraction studies. Electrochemical measurements such as cyclic-voltammetry and impedance spectroscopic measurements have provided the possible authentication on the stability of the electrochemical properties of the title material at shocked conditions so that MnFe_2O_4 NPs are proposed as a good fit for electronic device fabrication.

Declarations

Conflicts of interest

The authors declare that they have no conflict of interest.

Acknowledgements

The authors thank Department of Science and Technology (DST), India for funding through DST-FIST programme (SR/FST/College-2017/130 (c)). The project was supported by Researchers Supporting Project number (RSP-2021/231), King Saud University, Riyadh, Saudi Arabia.

References

1. A.M. Balagurov, I.A. Bobrikov, VYu. Pomjakushin, D.V. Sheptyakov, VYu. Yushankhai, Interplay between structural and magnetic phase transitions in copper ferrite studied with high-resolution neutron diffraction. *J. Magn. Magn. Mater.* 374 (2015) 591–599
2. A. Subha, M.G. Shalini, B. Sahu, S.C. Sahoo, Structural transformation and magnetic properties of copper ferrite nanoparticles prepared by sol–gel method. *J. Mater. Sci. Mater. Electron* 29 (2018) 20790–20799
3. Levy, D., Pavese, A., Hanfand, M.: Phase transition of synthetic zinc ferrite (ZnFe_2O_4) at high pressure from synchrotron X-ray powder diffraction. *Phys. Chem. Miner.* 27, (1999) 638–664
4. Zhang, J., Zhang, Y., Xiaoxin, Wu, Ma, Y., Chien, S.-Y., Guan, R., Dongzhou, Z., Yange, B., Yan, B., Yang, J.: Correlation between structural changes and electrical transport properties of spinel ZnFe_2O_4 nanoparticles under high pressure. *ACS Appl. Mater. Interfaces* 201 (2018) 42856–42864
5. Lijin Ye, Shuangmeng Zhai, Xiang Wu, Chaowen Xu, Ke Yang, Yuji Higo; Compressibilities of MnFe_2O_4 polymorphs. *Phys. Chem. Miner.* 42 (2015) 569–577.
6. Denis Andrault, Nathalie Bolfan; High-pressure phase transformations in the MgFe_2O_4 and Fe_2O_3 – MgSiO_3 systems. *Phys. Chem. Miner.* 28 (2001) 211–217.
7. Laura uenver-ThieLe, B. Lan, WoodLand, tiziana boffa BaLLaran, No buyoshi MiyajiMa, and dan J. Frost; Phase relations of Fe-Mg spinels including new high-pressure post-spinel phases and implications for natural samples. *Am. Mineral* 102 (2017) 2054–2064.

8. Zhongwu Wang, R. T. Downs, V. Pischedda, R. Shetty, S.K. Saxena, C.S. Zha, Y. SZhao, D.Schiferl and A. Waskowska: High-pressure x-ray diffraction and Raman spectroscopic studies of the tetragonal spinel CoFe_2O_4 . *Phys.Rev.B* 68 (2003) 094101
9. J. Blasco, G. Subías, J.García, C.Popescu, V.Cuartero: High-pressure transformation in the cobalt spinel ferrites; *J. Solid. State. Chem* 221 (2015) 173
10. F. D. Saccone, S. Ferrari, D. Errandonea, F. Grinblat, V. Bilovol, and S. Agouram: Cobalt ferrite nanoparticles under high pressure. *J.Appl.Phys* 118 (2015) 075903
11. Zhenyu Wu, Zhongxing Bao, Li Cao, Cuixia Liu, Qianshu Li, Sishen Xie, and Bingsuo Zou: Electrical properties and phase transition of CoFe_2O_4 nanocrystals under pressure. *J.Appl.Phys* 93 (2003) 9983
12. G.A.M. Amin, N.M. Spyrou; Study of gamma-radiation-induced optical effects in Ge–Se–Cd for possible industrial dosimetric applications. *Radiat. Phys. Chem.* 72 (2005) 419–422
13. A.Sivakumar, S.Suresh, S.Balachandar, S.A.Martin Britto Dhas; Effect of Shock Waves on Dielectric Properties of KDP Crystal, *J. Elect. Mat.* 47 (2018) 4381-4389
14. A.Sivakumar, S.Suresh, S.Balachandar, J.Thirupathy, J.Kalayana Sundar, S.A.Martin Britto Dhas; Effect of Shock Waves on Thermophysical properties of ADP and KDP crystals *Optic.Laser.Tech* 111 (2018) 284-289
15. A.Sivakumar, A.Saranraj, S.Sahaya Jude Dhas and S.A.Martin Britto Dhas; Shock wave induced enhancement of optical properties of benzyl crystal. *Mater. Res. Express* 6 (2019) 046205
16. Shamal L. Chinke, Inderpal Singh Sandhu, D. R. Saroha, and Prashant S. Alegaonka; Graphene-Like Nanoflakes for Shock Absorption Applications. *ACS Appl. Nano Mater.* 1, (2018) 6027–6037
17. A. Sivakumar, A. Rita, S. Sahaya Jude Dhas, S.A. Martin Britto Dhas; Tuning of surface plasmon resonance of silver nano particles by shock waves for plasmonic device applications. *Optic.Laser. Technol* 128 (2020) 106235
18. S.C. Hu, J. W. Huang, Z. Y. Zhong, Y. Y. Zhang, Y. Cai , and S. N. Luo; Texture evolution in nanocrystalline Cu under shock compression. *J. Appl. Phys.* 127 (2020) 215106
19. A. Sivakumar, S.Reena Devi, S. Sahaya Jude Dhas, R. Mohan Kumar, K.Kamala Bharathi, and S. A. Martin Britto Dhas; Switchable Phase Transformation (Orthorhombic - Hexagonal) of Potassium Sulfate Single Crystal at Ambient Temperature by Shock Waves. *Cryst. Growth Des.*, 20 (2020) 7111–7119
20. Vishakantaiah Jayaram, Asha Gupta, K.P.J.Reddy; Investigation of strong shock wave interactions with CeO_2 ceramic. *J.Adv.Ceram* 3 (2014) 297–305
21. S. Kalaiarasi, A. Sivakumar, S.A. Martin Britto Dhas, M. Jose; Shock wave induced anatase to rutile TiO_2 phase transition using pressure driven shock tube *Mater. Lett* 219, (2018) 72–75
22. V. Jayaram, K. P. J. Reddy; Experimental study of the effect of strong shock heated test gases with cubic zirconia. *Adv. Mater. Lett.* 7 (2016) 100-150

23. A. Sivakumar, S. Soundarya, S. Sahaya Jude Dhas, K. Kamala Bharathi, and S. A. Martin Britto Dhas; Shock Wave Driven Solid State Phase Transformation of Co_3O_4 to CoO Nanoparticles. *J.Phys.Chem.C* 124 (2020) 10755–10763
24. V. Mowlika, A. Sivakumar, S. A. Martin Britto Dhas, C. S. Naveen, A. R. Phani, R. Robert; Shock wave-induced switchable magnetic phase transition behaviour of ZnFe_2O_4 ferrite nanoparticles. *J. Nanostruc.Chem* 10 (2020) 203–209
25. V. Mowlika, C. S. Naveen, A. R. Phani, A. Sivakumar, S. A. Martin Britto Dhas, R. Robert; Crystallographic and magnetic phase stabilities of NiFe_2O_4 nanoparticles at shocked conditions. *J.Mater.Sci: Mater.Electron* 31 (2020) 14851–14858
26. A. Sivakumar, S. Sahaya Jude Dhas, S.A. Martin Britto Dhas; Assessment of crystallographic and magnetic phase stabilities on MnFe_2O_4 nano crystalline materials at shocked conditions. *Solid State.Sci* 107 (2020) 106340
27. Jitendra S. Kounsalye, Prashant B. Kharat, Dhananjay N. Bhoyar, K. M. Jadhav; Radiation-induced modifications in structural, electrical and dielectric properties of Ti^{4+} ions substituted $\text{Li}_{0.5}\text{Fe}_{2.5}\text{O}_4$ nanoparticles. *J. Mater. Sci: Mater.Electron* 29 (2018) 8601–8609
28. Hammam Abdurabu Thabit, Norlaili A. Kabir; The study of X-ray effect on structural, morphology and optical properties of ZnO nanopowder. *Nucl Instrum Meth B* 436 (2018) 278–284
29. A. Sivakumar, M. Manivannan, S. Sahaya Jude Dhas, J. Kalyana Sundar, M. Jose and S.A. Martin Britto Dhas; Tailoring the dielectric properties of KDP crystals by shock waves for microelectronic and optoelectronic applications. *Mater. Res. Express* 6 (2019) 086303
30. A.Sivakumar, S.Sahaya Jude Dhas, S.Balachandar and S.A.Martin Britto Dhas; Effect of shock waves on structural and dielectric properties of ammonium dihydrogen phosphate crystal. *Z. Kristallogr.* 234 (2019) 557–567
31. Monalisa Pal, Rupali Rakshit, and Kalyan Mandal; Surface Modification of MnFe_2O_4 Nanoparticles to Impart Intrinsic Multiple Fluorescence and Novel Photocatalytic Properties. *ACS Appl. Mater. Interfaces* 6 (2014) 4903–4910
32. Wei Wang, Zui Ding, Xiruo Zhao, Sizhu Wu, Feng Li, Ming Yue, and J. Ping Liu; Microstructure and magnetic properties of MFe_2O_4 (M = Co, Ni, and Mn) ferrite nanocrystals prepared using colloid mill and hydrothermal method. *J.Appl.Phys* 117 (2015) 328
33. Xing-Yu Long, Jia-Yuan Li, Dong Sheng, Hong-Zhen Lian; Spinel-type manganese ferrite (MnFe_2O_4) microspheres: A novel affinity probe for selective and fast enrichment of phosphopeptides. *Talanta* 166 (2017) 36–45
34. S.Meenakshi, S.Anitha, A.Sivakumar, S.A.Martin Britto Dhas, C.Sekar; Shock waves exposed $\alpha\text{-Fe}_2\text{O}_3$ Nanoparticles for electrochemical sensing of Riboflavin, Uric acid and Folic acid. *Microchemical Journal* 168 (2021) 160403,
35. P. Annie Vinosha, R. Ragu, S. Kalaiarasi, Belina Xavier, S. Jerome Das; Shock Induced TiO_2 Nanoparticles And Its Synergistic Effect In Photovoltaic Application. *Chem.Phys.Lett* 754 (2020)

36. Galinetto,P; Albini,B.; Bini,M.; and Mozzati, M.C. Raman Spectroscopy in Zinc Ferrites Nanoparticles; OpenTech **2018** DOI: <http://dx.doi.org/10.5772/intechopen.72864>
37. Xu Zuoa, Bernardo Barbiellinib, Carmine Vittoria; Calculation of exchange constants in manganese ferrite (MnFe_2O_4). J.Magn. Magn. Mater 272 (2004) 306–311
38. A. Sivakumar, S. Sahaya Jude Dhas, T. Pazhanivel, Abdulrahman I. Almansour, Raju Suresh Kumar, Natarajan Arumugam, C. Justin Raj, and S. A. Martin Britto Dhas. Phase Transformation of Amorphous to Crystalline of Multiwall Carbon Nanotubes by Shock Waves. Cryst. Growth Des. 21 (2021) 1617–1624

Figures

Figure 1

Raman spectra of the control and shocked MnFe₂O₄ NPs

Figure 2

Zoomed version of the control and shocked MnFe₂O₄ NPs

Figure 3

Raman shifts of F_{2g} (1), E_g and F_{2g} (2) with respect to the number of shock pulses

Figure 4

CV curves of the control and shocked MnFe₂O₄ NPs

Figure 5

Plots of specific capacitance of the control and shocked MnFe_2O_4 NPs with respect to the scan rates

Figure 6

(a) Comparison of CV curves of the control and shocked samples at 100 mVs⁻¹ (b) The values of specific capacitance with respect to the number of shock pulses

Figure 7

Cole – Cole plots of the control and shocked MnFe₂O₄ NPs

Figure 8

Zoomed version Cole – Cole plots of the control and shocked MnFe_2O_4 NPs