Morphological and optical investigations of the NiZnFe$_2$O$_3$ quaternary alloy nanostructures for potential application in optoelectronics

Asaad T. Al-Douri$^{a,b}$, A. S. Ibraheam$^{c,d}$, R. Gdoura$^a$, Y. Al-Douri$^{e,f,g,h}$ and A.F. Abd El-Rehim$^i$

$^a$Laboratoire de Recherche Toxicologie Microbiologie Environnementale et Santé (LR17ES06), Département des Sciences de la Vie, Faculté des Sciences de Sfax, Université de Sfax, Sfax, Tunisie; $^b$Department of Dental Industry, College of Medical Technology, Al-Kitab University, Kirkuk, Iraq; $^c$Iraqi Ministry of Education, Rumadi, Iraq; $^d$College of Science, Al-Anbar University, Rumadi, Iraq; $^e$Nanotechnology and Catalysis Research Center (NANOCAT), University of Malaya, Kuala Lumpur, Malaysia; $^f$Department of Mechatronics Engineering, Faculty of Engineering and Natural Sciences, Bahcesehir University, Istanbul, Turkey; $^g$Physics Department, Faculty of Science, University of Sidi-Bel-Abbes, Sidi-Bel-Abbes, Algeria; $^h$Engineering Department, American University of Iraq Sulaimani, Kurdistan, Iraq; $^i$Physics Department, Faculty of Science, King Khalid University, Abha, Saudi Arabia.

ABSTRACT

Nanostructure such as quaternary alloy offers an unprecedented opportunity for alloy composition control in a wide range, unavailable with traditional epitaxial film materials. The technique of chemical co-precipitation has been employed to synthesize the NiZnFe$_2$O$_3$ quaternary alloy nanostructure, which is cost-effective and friendly environmentally. The study of morphology for the mentioned NiZnFe$_2$O$_3$ quaternary alloy nanostructure is elaborated by scanning electron microscopy (SEM) to measure the grain size. The optical properties are investigated via UV-visible spectrophotometry (UV-vis) and Fourier-transform infrared spectroscopy (FTIR) to research the absorption, transmission, reflection, bandgap for the mentioned NiZnFe$_2$O$_3$ quaternary alloy nanostructure, also, for verifying optical dielectric constant and refractive index models using specific empirical models. The results show that the size and energy gap are investigated to recommend the suitability results for NiZnFe$_2$O$_3$ quaternary alloy nanostructure. Finally, Ravindra et al. models are appropriate for potential application in optoelectronics.

1. Introduction

Quaternary alloys have the potential for optoelectronic applications, and they are crystallized usually as tetragonal or cubic structures [1,2]. The industry of optoelectronics has grown rapidly during the last decades [3], and 80–90% of the solar cell technology is dominated by silicon-based materials that is proved to be a solid technology in the PV modules, due to cost-effectiveness and abundance of the used silicon in bulk (first generation), thin film (second generation) and some of the nanostructured (third generation) solar cells [4]. Advancements in the area of concentrating photovoltaics (CPVs) give best solar energy-to-electricity conversion efficiency [5], and also other investigations in perovskite photovoltaics reveal the exceptional light-absorbing properties exhibited by organometallic halides, which are chemical compounds that contain bonds between organic compounds and metal [6].

Ceramic-based quaternary II–VI materials are popular due to their high characteristics of structure and applicability for optoelectronics and others [7]. The NiZnFe$_2$O$_3$ quaternary alloy nanostructure comprises tetrahedral materials of chalcopyrite structure optoelectronics. Other ternary [8], quaternary [9] and quaternary [10,11] alloys have been researched. The bandgap of 2.5 eV is direct with non-toxic and abundant elements [12]. It is very important that the size and shape of nanostructure may affect the function and performance of optoelectronics. Specific methods have explored quaternary alloys and effective techniques have been utilized to prepare the alloys such as solvothermal [13], radio-frequency magnetron sputtering [14], sequential electrodeposition [15], ultrasonic spray pyrolysis [16] and electroanalysis [17]. The spin coating technique shows a direct correlation between high annealing temperature and crystallite size [1]. The NiZnFe$_2$O$_3$ quaternary alloy nanostructure has been synthesized by the chemical co-precipitation technique. The optical characteristics complement extravagantly for the interface studies. Many techniques, such as absorption, reflection, transmission and absorption coefficient permit in situ applications, and if applied in the FTIR, show quantitative information on an analytical and application level [17].
The photocatalytic and fluorescence sensing applications of manganese-doped zinc oxide nanostructures, synthesized by the solution combustion technique, using zinc nitrate as an oxidizer and urea as a fuel, are reported. The synthesized Mn-doped ZnO nanostructures have been analysed in terms of their surface morphology, phase composition, elemental analysis and optical properties [18]. But, Ag/AgVO3@CdS/BiVO4 heterostructure photocatalysts, by the photoreduction strategy and tested for H2 evolution under artificial solar irradiation, were synthesized by Mandari et al. [19]. The effects of Ag/AgVO3@CdS/BiVO4 heterostructure on the crystal phase, visible absorption, morphology, strong interactions and charge carrier separations were analysed by a series of characterization techniques. Based on the photocatalytic test, 1Ag/AgVO3@CdS/BiVO4 exhibited highest solar light-driven activity for hydrogen production (105.541 μmol/g) and with an apparent quantum yield. And, Ni100−xFex alloy catalysts are an alternative to Pt-based catalysts for the hydrogen evolution reaction (HER) in water electrolysis [20]. For optimum bonding and adhesion stability between a carbon paper (CP) electrode and Ni100−xFex alloy particles, the latter (obtained by varying the Ni/Fe ratio) is directly grown onto the CP electrode hydrothermally. The shape, crystallinity, and electrochemical properties of the alloy particles were analysed using electron spectroscopy, transmission electron microscopy, X-ray diffraction, Raman spectroscopy, X-ray photoelectron spectroscopy (XPS), and linear sweep voltammetry (LSV).

Heterostructures have been analysed in terms of their surface morphology, phase composition, elemental analysis and optical properties [18]. But, Ag/AgVO3@CdS/BiVO4 heterostructure photocatalysts, by the photoreduction strategy and tested for H2 evolution under artificial solar irradiation, were synthesized by Mandari et al. [19]. The effects of Ag/AgVO3@CdS/BiVO4 heterostructure on the crystal phase, visible absorption, morphology, strong interactions and charge carrier separations were analysed by a series of characterization techniques. Based on the photocatalytic test, 1Ag/AgVO3@CdS/BiVO4 exhibited highest solar light-driven activity for hydrogen production (105.541 μmol/g) and with an apparent quantum yield. And, Ni100−xFex alloy catalysts are an alternative to Pt-based catalysts for the hydrogen evolution reaction (HER) in water electrolysis [20]. For optimum bonding and adhesion stability between a carbon paper (CP) electrode and Ni100−xFex alloy particles, the latter (obtained by varying the Ni/Fe ratio) is directly grown onto the CP electrode hydrothermally. The shape, crystallinity, and electrochemical properties of the alloy particles were analysed using electron spectroscopy, transmission electron microscopy, X-ray diffraction, Raman spectroscopy, X-ray photoelectron spectroscopy (XPS), and linear sweep voltammetry (LSV).

Single-phase equi-atomic (Al0.2Co0.2Fe0.2Mn0.2Ni0.2)3O4 high-entropy oxide (HEO), having spinel ring, the solution is cooled to room temperature. The obtained material is NiZnFe2O3 quaternary alloy nanoparticle used for further analysis and characterization. The process is as follows:

1. The first step is to dissolve 1 gram of dried Gujarat, which is a short-sized plant herb with soft, green, deli-cate stem without woody tissues, in 100 ml of distilled water for 30 min. followed by dissolving zinc nitrate of molecular weight of 241.86 in distilled water for 30 min. and 60°C using [34]

\[
M = \frac{1000W}{Molecular \ weight \ V}
\]

where \(W\) is the weight, equal to 18.939 m, and \(V\) is the volume. The two solutions are mixed via a stirrer for 30 min. to obtain the nanocomposite.

2. The second step is to dissolve 1 g of dried Gujarat in 100 ml of distilled water for 30 min., followed by dissolving iron nitrate of molecular weight of 24.86 in distilled water for 30 min. and 60°C using equation (1). The two solutions are mixed via a stirrer for 30 min. to obtain the nanocomposite. The nickel nitrate of molecular weight of 189.39 in distilled water for 30 min. and 60°C using [34]

\[
M = \frac{1000W}{Molecular \ weight \ V}
\]

where \(W\) is the weight, equal to 18.939 m, and \(V\) is the volume. The two solutions are mixed via a stirrer for 30 min. to obtain the nanocomposite. The second step is to dissolve 1 g of dried Gujarat in 100 ml of distilled water for 30 min., followed by dissolving iron nitrate of molecular weight of 24.86 and ferrous nitrate (Fe(NO3)2.9H2O) and ferric nitrate (Fe(NO3)3.9H2O) are in molar ratio 1:1:2 to reach the optimum synthesized materials. For the detailed green synthesis process, the chemical co-precipitation approach has been carried out. Under constant stirring, the solution is cooled to room temperature. The obtained material is NiZnFe2O3 quaternary alloy nanoparticle used for further analysis and characterization. The process is as follows:

3. The second step is to dissolve 1 gram of dried Gujarat, which is a short-sized plant herb with soft, green, deli-cate stem without woody tissues, in 100 ml of distilled water for 30 min. followed by dissolving zinc nitrate of molecular weight of 241.86 in distilled water for 30 min. and 60°C using [34]

\[
M = \frac{1000W}{Molecular \ weight \ V}
\]

where \(W\) is the weight, equal to 18.939 m, and \(V\) is the volume. The two solutions are mixed via a stirrer for 30 min. to obtain the nanocomposite. The second step is to dissolve 1 g of dried Gujarat in 100 ml of distilled water for 30 min., followed by dissolving iron nitrate of molecular weight of 24.86 and ferris nitrate (Fe(NO3)3.9H2O) and ferric nitrate (Fe(NO3)3.9H2O) are in molar ratio 1:1:2 to reach the optimum synthesized materials. The detailed green synthesis process, the chemical co-precipitation approach has been carried out. Under constant stirring, the solution is cooled to room temperature. The obtained material is NiZnFe2O3 quaternary alloy nanoparticle used for further analysis and characterization. The process is as follows:

The green approach for synthesizing nanoparticles is always better due to eco-friendliness [33]. All solvents and chemicals are obtained from Sigma-Aldrich (USA, http://www.sigmaaldrich.com). The solutions of aqueous salt for nickel nitrate, cobalt nitrate, magnesium nitrate, zinc nitrate or (CH3COO)2.Zn,2H2O) and ferric nitrate (Fe(NO3)3.9H2O) are in molar ratio 1:1:2 to reach the optimum synthesized materials. For the detailed green synthesis process, the chemical co-precipitation approach has been carried out. Under constant stirring, the solution is cooled to room temperature. The obtained material is NiZnFe2O3 quaternary alloy nanoparticle used for further analysis and characterization. The process is as follows:

1. The first step is to dissolve 1 gram of dried Gujarat, which is a short-sized plant herb with soft, green, deli-cate stem without woody tissues, in 100 ml of distilled water for 30 min. followed by dissolving zinc nitrate of molecular weight of 241.86 in distilled water for 30 min. and 60°C using [34]

\[
M = \frac{1000W}{Molecular \ weight \ V}
\]

where \(W\) is the weight, equal to 18.939 m, and \(V\) is the volume. The two solutions are mixed via a stirrer for 30 min. to obtain the nanocomposite.

2. The second step is to dissolve 1 g of dried Gujarat in 100 ml of distilled water for 30 min., followed by dissolving iron nitrate of molecular weight of 24.86 and ferris nitrate (Fe(NO3)3.9H2O) and ferric nitrate (Fe(NO3)3.9H2O) are in molar ratio 1:1:2 to reach the optimum synthesized materials. The detailed green synthesis process, the chemical co-precipitation approach has been carried out. Under constant stirring, the solution is cooled to room temperature. The obtained material is NiZnFe2O3 quaternary alloy nanoparticle used for further analysis and characterization. The process is as follows:

The last three solutions are added to the first and second steps mentioned upon to synthesize the quaternary alloy nanostructure. The optical properties are measured at room temperature using ultraviolet–
3. Results and discussion

3.1. Morphological study

Scanning electron microscopy (SEM) images of the NiZnFe$_2$O$_3$ quaternary alloy nanostructure are shown in Figure 1. The NiZnFe$_2$O$_3$ morphology presents agglomerated grains and small cubes. The formation of crystallites is dense for the NiZnFe$_2$O$_3$ quaternary alloy nanostructure. Figure 1 shows agglomerated particles and good and large nanostructures adhere to the surface due to the material content, the analogy is clear. The homogeneity of cube-like nanostructure is illustrated in NiZnFe$_2$O$_3$ image that reflects the crystallite size. The grain size is measured, as given in Table 1.

3.2. Optical properties

The optical studies are very important for the potential application in optoelectronics to illustrate the necessity of absorption, transmission, reflection, absorption coefficient and FTIR from analytical viewpoint.

3.2.1. Absorbance

The absorbance spectra of the NiZnFe$_2$O$_3$ quaternary alloy nanostructure are measured at ambient temperature via UV-vis in wavelength range of 350–1150 nm, as shown in Figure 2. The absorbance spectra are due to material behaviour. The correlation between absorption and wavelength is inverse.

3.2.2. Transmittance

The transmittance spectra are shown in Figure 2 of the NiZnFe$_2$O$_3$ quaternary alloy nanostructure in the wavelength range of 350–1150 nm. The transmittance is due to the inverse correlation with absorbance. The correlation between transmittance and wavelength is direct. The highest transmittance is below 1 a.u. NiZnFe$_2$O$_3$ quaternary alloy nanostructure.

3.2.3. Reflectance

The reflectance spectra are illustrated in Figure 2 for the NiZnFe$_2$O$_3$ quaternary alloy nanostructure in the wavelength range of 350–1150 nm. The increase of reflectance is due to the direct correlation with transmittance. The overview correlation between reflectance and wavelength is inverse. The highest reflectance is almost 0.2 a.u. at the NiZnFe$_2$O$_3$ quaternary alloy nanostructure.

3.2.4. Absorption coefficient

The absorption coefficient value is high for short wavelength, then begins to decline as the wavelength increases for the area between 350 and 390 nm of energy gap ($E_g$), as illustrated in Figure 3. This is meaning the photons absorption is direct, while the absorption breadth mentions to varied types of absorption, direct and indirect that are arisen of crystal structure changing correspond to different atomic numbers. The edge of absorption shifts towards ultraviolet as the atomic number increases. For the NiZnFe$_2$O$_3$ quaternary alloy nanostructure, the absorption edge is at 393 nm ($E_g = 3.15$ eV), as given in Table 1. The energy gap ($E_g$) of the NiZnFe$_2$O$_3$ quaternary alloy nanostructure is determined via direct transition between the valance and conduction bands. The edge of absorption follows the exponential law. The absorption coefficient obeys [11].

$$\alpha \nu = A (\nu - E_g)^n$$

where constant refers to $A$, bandgap refers to $E_g$, and 1/2 refers to $n$, as illustrated in Figure 3.

Table 1. Grain size, bandgap corresponding to refractive index and optical dielectric constant of the NiZnFe$_2$O$_3$ quaternary alloy nanostructure.

| Alloy       | Grain size (nm) | $E_g$ (eV) | $n$   | $\epsilon_\infty$ | References |
|-------------|----------------|-----------|-------|-------------------|------------|
| NiZnFe$_2$O$_3$ | 44.80         | 3.15      | 2.09$^a$2.30$^b$2.33$^c$ | 4.36$^a$5.29$^b$5.42$^c$ | $^a$Ref. [35];$^b$Ref. [36];$^c$Ref. [37]. |
Figure 2. Absorbance, transmittance and reflectance of the NiZnFe₂O₃ quaternary alloy nanostructure.
The difference in $E_g$ is due to parameters, such as the precursors' nature and concentration, granular structure, crystal structure and structural defects as well as differences in grain boundaries and imperfections in polycrystallines [11]. The physical factor of refractive index $n$ is important. From theory viewpoint, $n$ is related to local polarizability and density [35]. Different relationships of $n$ and $E_g$ have been reported [36–43] to validate our current work. Ravindra et al. [35] have presented a direct correlation between high-frequency refractive index and $E_g$:

$$n = \alpha + \beta E_g,$$

(3)

where $\alpha = 4.048$ and $\beta = 0.62 \text{ eV}^{-1}$. But, Herve and Vandamme [36] have suggested another relation as

$$n = \sqrt{1 + \left(\frac{A}{E_g + B}\right)^2},$$

(4)

$A = 13.6 \text{ eV}$ and $B = 3.4 \text{ eV}$. And, Ghosh et al. [37] had considered another approach of Penn [44] and Van Vechten [45]. $A$ is contributed from valence electrons and $B$ is added to $E_g$ to present the following:

$$n^2 - 1 = A/(E_g + B)^2,$$

(5)

$A = 25E_g + 212$, $B = 0.21E_g + 4.25$ and $(E_g + B)$. Therefore, the mentioned models of $n$ and $E_g$ are researched. Also, the optical dielectric constant ($\epsilon_\infty$) is obtained via $\epsilon_\infty = n^2$ [45]. The calculated $n$ and $\epsilon_\infty$ are displayed in Table 1. This proves that the Ravindra et al. model is an appropriate for the potential application of optoelectronics.

### 3.2.5. FTIR

To investigate the chemical interaction of the NiZnFe$_2$O$_3$ quaternary alloy nanostructure, the Fourier-transform infrared spectroscopy (FTIR) analysis is achieved in the range of 400–4000 cm$^{-1}$, as shown in Figure 4 corresponding to the stretching vibrations. FTIR and its corresponding data are recoded. It is obtained for the NiZnFe$_2$O$_3$ quaternary alloy nanostructure, as demonstrated in Figure 4. For the NiZnFe$_2$O$_3$ quaternary alloy nanostructure, weak absorption band is presented at 3244.27 cm$^{-1}$ that is attributed to vibrations of OH stretching water. Very weak vibration is shown at 2380.16, 2310.72, 2106.27, 1832.38 and
1743.65 cm$^{-1}$ of stretching of C–C. A medium strong in 1635.64 cm$^{-1}$ is due to stretching vibrations [46]. The stretching vibration mode originates from the reaction intermediates or residues of acetates used for the preparation of the mentioned alloys. The broad absorption band is due to the stretching mode to confirm that ions are introduced in the sites. The electrochemical contribution is important for different technological applications. The optoelectronic devices are important in energy storage to enable renewable energy conversion technologies for giving a direct relationship between electricity generations and associated chemical changes in a reaction.

4. Conclusions

The NiZnFe$_2$O$_3$ quaternary alloy nanostructure was synthesized using chemical the co-precipitation technique. Improvement in morphological studies toward homogenous-formed nanograins was noted. The grain size was 44.80 nm. Furthermore, the bandgap was 3.15 eV. The spectroscopic results were obtained and clusters’ mean size has recommended the formation intermediates or residues of acetates used for the preparation of the mentioned alloys. The broad absorption band might be due to the stretching mode to confirm that ions are introduced in the sites. The electrochemical contribution is important for different technological applications. The optoelectronic devices are important in energy storage to enable renewable energy conversion technologies for giving a direct relationship between electricity generations and associated chemical changes in a reaction.

Acknowledgements

One of us, A.F. Abd El-Rehim extends his appreciation to the Deanship of Scientific Research at King Khalid University for funding this work through research groups program under grant number R.G.P. 2/69/42.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Y. Al-Douri @ http://orcid.org/0000-0002-5175-6372

References

[1] Odeh AA, Al-Douri Y, Ayub RM, et al. Optical analysis of lens-like Cu$_2$ CdSnS$_4$ quaternary alloy nanostructures. Appl Phys A. 2016;122:888–902.
[2] Matsushita H, Katsui A. Materials design for Cu-based quaternary compounds derived from chalcopyrite-rule. J Phys Chem Solids. 2005;66:1933–1936.
[3] Saidan M, Albaali AG, Alasai E, et al. Experimental study on the effect of dust deposition on solar photovoltaic panels in desert environment. Renew Energy. 2016;92:499–505.
[4] Ali N, Hussain A, Ahmed R, et al. Advances in nanostructured thin film materials for solar cell applications. Renew Sustain Energy Rev. 2016;59:726–737.
[5] Vossier A, Chemisana D, Flamant G, et al. Very high fluxes for concentrating photovoltaics: considerations from simple experiments and modeling. Renew Energy. 2012;37:31–39.
[6] Petrović M, Chellappan V, Ramakrishna S. Perovskites: solar cells and engineering applications – materials and device developments. Sol Energy. 2015;122:678–699.
[7] Qiu C, Hu Y, Jin Z, et al. A review of green techniques for the synthesis of size-controlled starbed-based nanoparticles and their applications as nanodelivery systems. Trends Food Sci Technol. 2019;92:138–151.
[8] Gherab K, Al-Douri Y, Hashim U, et al. Temperature effect to investigate optical and structural properties of AZO nanostructures for optoelectronics. Bull Mater Sci. 2021;44:39–48.
[9] Al-Douri Y, Odeh AA, Johan MR, et al. Synthesis and characterization of Cu$_2$CdSnS$_4$ quaternary alloy nanostructures. Int J Electrochem Sci. 2018;13:6693–6707.
[10] Ibraheam AS, Al-Douri Y, Voon CH, et al. Surface functionalyzed Cu$_2$Zn$_{1−x}$Cd$_x$Sn$_4$ quaternary alloy nanostructure for DNA sensing. Appl Phys A. 2017;123:200–208.
[11] Ibraheam AS, Al-Douri Y, Mohammed AS, et al. Electrical, optical and structural properties of Cu$_2$Zn$_{1−x}$Cd$_x$Sn$_4$ quaternary alloy nanostructures synthesized by spin coating technique. Int J Electrochem Sci. 2015;10:9863–9876.
[12] Bacewicz R, Antonowicz J, Podsiadlo S, et al. Local structure in Cu$_2$ZnSn$_4$S$_4$ studied by the XAFS method. Solid State Commun. 2014;177:54–67.
[13] Meng L, Li Y, Yao B, et al. Visible-blind ultraviolet photodetector based on p-Cu$_2$CdSnS$_4$/n-ZnS heterojunction with a type-I band alignment. J Phys D. 2016;50:235306–235315.
[14] Shi L, Wu C, Ding J. Nanoconfined solvothermal synthesis, formation mechanism and photoresponse properties of Cu$_2$CdSnS$_4$ nanowires array. J Alloys Compd. 2016:683:46–57.
[15] Pawara SM, Pawara BS, Moholkar AV, et al. Single step electrosynthesis of Cu$_2$ZnSnS$_4$ (CZTS) thin films for solar cell application. Electrochim Acta. 2010;55:4057–4068.
[16] He X, Shen H, Pi J, et al. Synthesis of Cu$_2$ZnSnS$_4$ films from sequentially electrodeposited Cu–Sn–Zn precursors and their structural and optical properties. J Mater Sci Mater Electron. 2013;24:4578–4589.
[17] Kermadi S, Sali S, Ait Ameur F, et al. Effect of copper content and sulfurization process on optical, structural and electrical properties of ultrasonic spray pyrolysed Cu$_2$ZnSnS$_4$ thin films. Mater Chem Phys. 2015;169:96–105.
[18] Thakur D, Sharma A, Awasthi A, et al. Manganese-doped zinc oxide nanostructures as potential scaffold for photocatalytic and fluorescence sensing applications. Chemosensors. 2020;8:120–129.
[19] Bacewicz R, Antonowicz J, Podsiadlo S, et al. Local structure in Cu$_2$ZnSn$_4$S$_4$ studied by the XAFS method. Solid State Commun. 2014;177:54–67.
[20] Lee J, Son N, Shin J, et al. Highly efficient hydrogen evolution reaction performance and long-term stability of spherical Ni100–xFex alloy grown directly on a carbon paper electrode. J Alloys Compd. 2021;869:159265–159274.
[21] Shaw SK, Gangwar A, Sharma A, et al. Structural and magnetic properties of nanocrystalline equi-atomic spinel high-entropy oxide (AlCoFeMnNi)$_2$O$_4$ synthesized by microwave assisted co-precipitation technique. J Alloys Compd. 2021;878:160269–160279.
[22] Crepaldi EL, Pavan PC, Valim JB. Comparative study of the coprecipitation methods for the preparation of layered double hydroxides. J Braz Chem Soc. 2000;11:898–912.

[23] Zhou X, Wang Z, Qu Y, et al. Electron mobility influenced by optical phonons in AlGaN/GaN MISHEMTs with different gate dielectrics. Appl Phys A. 2020;126:825–833.

[24] Sarac MF. Magnetic, structural, and optical properties of gadolinium-substituted Co0.5Ni0.5Fe2O4 spinel ferrite nanostructures. J Supercond Novel Magn. 2020;33:397–406.

[25] Goktas A, Tumbul A, Aba Z, et al. Enhancing crystalline/optical quality, and photoluminescence properties of the Na and Sn substituted ZnSn thin films for optoelectronic and solar cell applications; a comparative study. Opt Mater. 2020;107:110073–110082.

[26] Banerjee S, Chakravorty D. Synthesis and optical properties of nickel zinc ferrite nanoparticles grown within mesoporous silica template. AIP Conf Proc. 2012;1447:233–241.

[27] Tumbul A, Aslan F, Demirozu S, et al. Solution processed boron doped ZnO thin films: influence of different boron complexes. Mater Res Express. 2019;6:035903–035911.

[28] Judith Vijaya J, Bououdina M. Structural, optical and magnetic properties of Ni-Zn ferrite nanoparticle prepared by a microwave assisted combustion method. J Nanosci Nanotechnol. 2016;16:689–697.

[29] Goktas A, Aslan F, Mutlu IH. Effect of preparation technique on the selected characteristics of Zn1−xCoxO nanocrystalline thin films deposited by sol–gel and magnetron sputtering. J Alloys Compd. 2014;615:765–778.

[30] Chand P, Vaish S, Kumar P. Structural, optical and dielectric properties of transition metal (MFe2O4; M = Co, Ni and Zn) nanoferrites. Phys B. 2017;524:53–63.

[31] Goktas A, Aslan F, Tumbul A, et al. Tuning of structural, optical and dielectric constants by various transition metal doping in ZnO:TM (TM = Mn, Co, Fe) nanostructured thin films: a comparative study. Ceram Int. 2017;43:704–713.

[32] Fong CY, Ng SS, Yam FK, et al. Synthesis of wurtzite GaN thin film via spin coating method. Mater Sci Semicond Process. 2014;17:63–75.

[33] Abdolahad M, Janmaleki M, Mohajerzadeh S, et al. Polyphenols attached graphene nanosheets for high efficiency NIR mediated photodestruction of cancer cells. Mater Sci Eng C. 2013;33:1498–1505.

[34] Ibraheam AS, Al-Douri Y, Hashim U, et al. Cadmium effect on optical properties of Cu2Zn1−xCdxSnS4 quaternary alloys nanostructures. Sol Energy. 2015;114:39–50.

[35] Ravindra NM, Auluck S, Srivastava VK. On the Penn gap in semiconductors. Phys Status Solid. 1979;93:k155–k160.

[36] Herve PJL, Vandamme LKJ. Empirical temperature dependence of the refractive index of semiconductors. J Appl Phys. 1995;77:5476–5488.

[37] Ghosh DK, Samanta LK, Bhar GC. A simple model for evaluation of refractive indices of some binary and ternary mixed crystals. Infrared Phys. 1984;24:43–58.

[38] Al-Douri Y, Khachai H, Khenata R. Chalcogenides-based quantum dots: optical investigation using first-principles calculations. Mater Sci Semicond Process. 2015;39:276–282.

[39] Al-Douri Y, Hashim U, Khenata R, et al. Ab initio method of optical investigations of CdS1−xTex alloys under quantum dots diameter effect. Sol Energy. 2015;115:33–39.

[40] Al-Douri Y. Electronic and optical properties of ZnxCd1−xSe. Mater Chem Phys. 2003;82:49–54.

[41] Al-Douri Y, Feng YP, Huan ACH. Optical investigations using ultra-soft pseudopotential calculations of Si0.5Ge0.5 alloy. Solid State Commun. 2008;148:521–524.

[42] Al-Douri Y, Reshak AH, Baaziz H, et al. An ab initio study of the electronic structure and optical properties of CdS1−xTex alloys. Sol Energy. 2010;84:1979–1984.

[43] Penn DR. Wave-number-dependent dielectric function of semiconductors. Phys Rev. 1962;128:2093–2106.

[44] Van Vechten JA. Quantum dielectric theory of electronegativity in covalent systems. I. Electronic dielectric constant. Phys Rev. 1969;182:891–906.

[45] Samara GA. Temperature and pressure dependences of the dielectric constants of semiconductors. Phys Rev B. 1983;27:3494–3506.

[46] Wang Y, Gao X, Zhang W, et al. Synthesis of hierarchical CuS/RGO/PANI/Fe3O4 quaternary composite and enhanced microwave absorption performance. J Alloys Compd. 2018;757:372–381.