Phase transformation and size control of CdS and Fe/CdS nanoparticles prepared by pulsed laser ablation

A. S. Ahmed^{*}, A. B. Sharba, Q. M. Salman

University of Babylon, College of Science for Women, Department of Laser Physics, Hilla-Najaf Street, Babylon, 51002, Iraq

This work presents the synthesis and characterization of Homophase CdS and Heterophase Fe/CdS nanoparticles prepared by pulsed laser ablation (PLA) in water and methanol using nanosecond duration Nd:YAG laser. The morphology, the crystalline state, and the structure of the products were examined by performing SEM, XRD, and FTIR measurements, respectively. The results showed the transformation of the crystalline phase and changing the clustering size of CdS nanoparticles when performing PLA in methanol and water. Fe/CdS Heterojunctions were obtained in both liquids. The presence of Fe nanoparticle imposed another phase transformation and significantly improved the aggregation properties of the CdS nanoparticles.

(Received September 27, 2024; Accepted December 3, 2024)

Keywords: Fe, Fe/CdS, Laser ablation, Liquid effect, Phase transformation

1. Introduction

There is a great interest in Nano-scale forms of semiconductor materials due to their unique optical, electrical, and magnetic properties. These properties made Nano-size material become the core part of a large number of applications. Cadmium sulfide (CdS), a semiconductor material in the II-VI group, is a promising kind of semiconductor. It has distinct photochemical properties and a great ability to absorb visible light. Therefore, it has been used in a large number of technological applications including photoconductors, transistors, solar cells, light-emitting diodes (LEDs), lasers, displays, and photocatalysts [1]. However, single-phase CdS quantum dots are characterized by being optically unstable, which causes photo-corrosion during photo-catalysis [2]. To overcome this disadvantage, researchers resorted to form a hybrid structure of CdS with other semiconductors [3] or loading metal catalysts on the surface [4].

In addition, in the fields of renewable energy and photocatalytic applications, single semiconductors suffer from spectral narrowing and photo-generated carriers recombination [5]. Heterojunctions and Homojunctions structures have become a brilliant solution for these issues [6]. In this context, Heterojunctions/Homojunctions structures widen the spectral response region of the semiconductors by combining the absorption areas of multiple kinds of material and significantly reduce the electron-hole recombination by providing additional energy states for the electron represented by the different conduction bands of the combined phases or material. Based on this, a large number of Heterophase and Homophase structures have been synthesized and proposed [2]. As CdS is found in nature in the form of Wurtzite or Howlite structures [7], Homophase junction can be made by combining the two phases of this salt. Furthermore, hybridization of CdS with magnetic material can result in producing structures with dual functionality: extending the optical and electrical properties of the structures and providing magnetic control. Such a new class of hybrid Nano-structures can be used in superior applications [8,9].

In literature, many works studied improving the properties of CdS nanomaterial by hybridization. For example, A. M. Mansour et al. [10] showed that CdS preserves its cubic structure with slight change in the energy gap when doping with Fe_3O_4 via a mechanical grinding method. Tingting Cheng et al. [11] enhanced the photocatalytic activity of CdS to about 1.6 times

^{*} Corresponding author: angham.harbi.gsci168@student.uobabylon.edu.iq https://doi.org/10.15251/CL.2024.2112.989

by assembling CdS nanoparticles on $Bi_4Ti_3O_{12}$ surface. Furthermore, previous studies [12] indicated that CdS prepared by the chemical deposition method showed a single cubic phase. However, these studies indicated that CdS doped with Fe possesses superior catalytic potential compared to undenatured CdS. Xiaoyan Li et al. [13] presented the phase transition of CdS Nanoparticles from cubic to hexagonal by adding water to the melts. Phase transition of CdS nanoparticles from wurtzite to rocksalt was also revealed by Lingyao Meng et al. at high pressure [14].

Generally, the construction of Heterophase junctions required, first, synthesizing the two elements separately and subsequently binding them in, usually, complex, time consuming, and not environmentally friendly reactions. On the other hand, even forming Homojunctions does not involve combining different materials, controlling the properties of the Homojunctions is very difficult due to the similarity of their chemical structure. Therefore, there are few studies dealing with Homo-crystalline materials [2]. In comparison with the chemical methods, pulsed laser ablation in liquid (PLAL) methodology is a chemical free technique that is capable of producing high stability single and complex structures of nanomaterial in environmentally friendly nature [15, 16].

In this work, we present the synthesis and detailed structural characterization of CdS and Fe/CdS nanoparticles prepared by pulsed laser ablation in water and methanol. This study revealed the remarkable divergence of the CdS properties depending on the preparation conditions. In this context, we showed that the phase transformation and particle size control of CdS nanoparticles depend significantly on the liquid properties and the presence of iron particles. The results of this study indicated the possibility of fabricating Heterojunction/Homojunction nanostructures by using PLAL, which can be of great importance in a large number of applications.

2. Experimental part

All samples used in this work were prepared by using the PLAL process. The process included several basic steps. First, two separated discs, one of iron (Fe) and another of cadmium sulfide (CdS), were fabricated by mechanically pressing Fe and CdS solid powders by using a hydraulic press device with a stable pressure of (30 MPa). The thickness of the iron and cadmium sulfide discs were (4.36 mm) and (3.94 mm), respectively, each with a diameter of 20 mm. One of these discs was placed in a glass container filled with methanol, or distilled water, for preparing Fe and CdS nanoparticles. An Nd-YAG laser with a wavelength of (1064 nm), maximum energy of (500 mJ), 4.5 nsec pulse duration, and frequency of (4 Hz), was used with a 5 cm focal length lens for the ablation process. The number of laser pulses used was determined by the desired concentration of the nanoparticles. The container was covered with aluminum foil with a hole about the laser beam diameter to prevent the methanol from burning during the ablation process. As for the Fe/CdS samples, the iron disk was first placed in a glass container and bombarded with the laser. After that, the iron disc was removed and the CdS disc was placed in the same liquid and fired with the laser at the same conditions. The Fe/CdS nanoparticles were collected by using an external magnet. After collection, the particles were re-dispersed in a new liquid (methanol or water).

The shape and the size of the prepared nanoparticles were examined by performing scanning electron microscope (SEM) measurements using a Σ IGMA, JSM-7610F, Carl Zeiss device. The samples for this measurement were prepared by depositing a thin layer of the liquid containing the nanomaterial on a glass slide. The crystalline structure of the nanoparticles was investigated by performing X-ray diffraction (XRD) measurements using a (DX-2700BH) spectrometer analysis system produced by (Haoyuan Instrument Co., Ltd.) with a Silicon Drift Detector. The samples for this measurement were also prepared by depositing the nanomaterial on a glass slide but this time multiple layers were deposited in order to increase the amount of the material detected. As for the Fourier transform infrared (FTIR) spectroscopy we used a BRUKER FTIR spectrometer.

3. Results and discussion

3.1. Scanning Electron Microscopy (SEM) measurements

SEM measurement was conducted to examine the shape and size of the nanoparticles resulting from the laser ablation process. Figure (1) shows the image and the histogram of iron nanoparticles prepared in methanol. As can be seen from the figure, the particles are distinguishable with spherical or semispherical shapes. Also, the figure shows that the resulting nanoparticles do not clump together despite their proximity. The histogram in Figure (1 b) shows that the particles have a relatively narrow distribution ranging between 5-50 nm, with the largest number of particles having sizes ranging from 15-30 nm.



Fig. 1. (a) SEM image of Fe nanoparticles prepared in Methanol (b) Histogram of the image in part (a)

The shape and properties of the nanomaterial prepared by the laser ablation process depend mainly, in addition to the properties of the target material, on the parameters of the laser pulses used and the properties of the liquid used. The density, polarity, ability to form hydrogen bonds, and other physical and chemical properties of liquids may have direct and indirect effects on the properties of the material dissolved or suspended in these liquids [17-19]. The effect of the properties of the liquid may be different or have different significance depending on the target material and the preparation conditions. Figure (2) shows the shape and the histogram of iron particles prepared under the same conditions as those in Figure (1), but the liquid used is distilled water.



Fig. 2. (a) SEM image of Fe nanoparticles prepared in water (b) Histogram of the image in part (a).

The figure shows that, in terms of shape, the shape of the iron particles prepared in distilled water does not differ much from the shape of the particles prepared in methanol. The size distribution of particles prepared in distilled water is slightly shifted towards larger sizes compared to the statistics of the particles prepared in methanol. The Gaussian size distribution of the particles seems to be regular. This may attributed to the uniformity and stability of the preparation conditions during the processes of laser ablation and particle nucleation in water.

It is worth noting that iron particles prepared in water and methanol retain their magnetic properties in terms of responding to the external magnetic field. However, what is noticed about the properties of the prepared particles is that they are closer to the properties of superparamagnetic particles, as the extent of their magnetic hysteresis is relatively weak. This was noticed by observing the speed of re-diffusion of the particles in the liquid after removing the applied external magnetic field. This case was observed on samples prepared in water and methanol. However, confirming the generation of iron particles with superparamagnetic properties requires further investigation and tests, such as conducting vibrating-sample magnetometer (VSM) measurements.

Figure (3) shows the SEM image and the histogram of cadmium sulfide particles prepared in methanol.



Fig. 3. (a) SEM image of CdS nanoparticles prepared in Methanol (b) Histogram of the image in part (a).

The figure shows large clusters extending over the entire area of the sample prepared for the SEM examination. It can be seen that these aggregates consist of clustering of relatively small spherical or semispherical nanoparticles, with sizes ranging between 10-40 nm, as shown in Figure (3b). The aggregation of these particles at this size, when compared with the shape and stability of nanoparticles suspended in the liquid, suggests that this aggregation occurred when the sample was prepared for the SEM examination and not when the particles were dispersed in the liquid. In other words, the suspended particles in methanol do not suffer this level of aggregation. In addition, this assembly indicates that the CdS particles formed in methanol have no surface charge; hence, they aggregate in large clusters. Furthermore, the shape of the assembly of these particles is random and does not represent any crystalline formation or uniform arrangement. This does not prevent that the aggregated nanoparticles are mainly composed of mono or polycrystalline nano-sized crystals.

Interestingly, the CdS particles formed in water are assembled into perfect and very regular crystalline cubes, as shown in Figure (4). What is more interesting is that, the size of these formations seems to be identical, as can be seen from Figure (4 b). The average side length of these structures is about 370 nm.



Fig. 4. (a) (b) SEM images of CdS nanoparticles prepared in Water with different scales, (c) Histogram of the image in parts (a) and (b).

As can be seen from Figure (4a), the cubic formations consist of or are decorated with particles of a narrow size distribution, as shown in part (c) of Figure (4). On the other hand, by looking at the distribution of these cubic structures and the spacing between them, it is clear that these cubic structures were formed during or after the process of producing the particles by the laser ablation process in liquid. That is, these structures result from the accumulation of free-moving nanoparticles but not during the process of preparing the SEM samples. In addition to these structures, the CdS sample prepared in water contains individual nanoparticles dispersed in the liquid and not formed into crystalline or random structures.

Hybridization or encapsulation of nanomaterial leads to noticeable changes in their properties, as well as obtaining a new and improved combination of properties that cannot be obtained from single nanomaterial. Figures (5) and (6) show the SEM images and histograms of cadmium sulfide particles connected to iron particles prepared in methanol and water, respectively.



Fig. 5. (a) SEM image of Fe-CdS nanoparticles prepared in Methanol (b) Histogram of the image in part (a).



Fig. 6. (a) SEM image of Fe/CdS nanoparticles prepared in water (b) Histogram of the image in part (a).

Comparing the SEM images in Figures (5) and (6) shows no clear differences between the two shapes despite the difference in the properties of the two liquids. Particles in both cases are spherical or close to that, distributed homogeneously and individually, despite their close proximity. Moreover, the size distributions of both samples are very close, with a very slight shift of the sample prepared in methanol towards smaller sizes. However, the size distribution of these particles is clearly shifted towards small sizes compared to the size distribution of pure CdS particles. This can be considered as one of the important properties that can be obtained from the hybridization of CdS and Fe.

The deviation towards the small size distribution of the hybrid material could be due to the accumulation of the molecules of one substance on the surface of the other, which prevents particle aggregation. This property is considered as one of the very important properties in the world of nanomaterial because it means longer-term stability for nanomaterial suspended in liquids. Looking at Figures (5) and (6), it can be seen that the cadmium sulfide particles in methanol did not clump in the liquid, not even when the sample was deposited for the purpose of preparing the SEM slides. This could indicate the generation of a surface charge on the surfaces of the hybrid nanomaterial formed in methanol. Such a phenomenon could be due to charge transfer or charge redistribution between the two superimposed materials. In addition, the low level of aggregation of the hybrid nanoparticles could be due to the saturation of the surface of one substance by bonding with the other substance.

It can also be noticed that no clear crystalline structure is formed from cadmium sulfide particles in water when hybridized with iron particles. This clear change in the character of the nanomaterial indicates a strong effect of particle hybridization. On the other hand, the hybridization of cadmium sulfide particles and iron particles did not affect the magnetic properties of the iron particles at all.

3.2. FTIR examination results

Figure (7) displays the FTIR spectra of CdS, iron, and Fe/CdS nanoparticles.



Fig. 7. FTIR spectra of (a) Fe3O4, (b) CdS, and (c) Fe3O4/CdS connected nanoparticles.

All the spectra contain known absorption bands that belong to the stretching and bending vibrations of O-H, C-H, CH₂, C-N, and C=O [10, 20, 21], as shown in Figure (7). Pure iron particles generated in water and methanol are highly unlikely to survive as pure iron particles due to the formation of a layer of iron oxide around them. Spectrum (a) in Figure (7) represents the FTIR spectrum of iron nanoparticles. This spectrum clearly shows the formation of a layer of iron oxide on iron nanoparticles. The band between 400-650 cm⁻¹ is a characteristic feature of Fe-O in the Fe₃O₄ molecule [22]. This band is centered at 588 cm⁻¹ and corresponds to the stretching vibration of Fe-O in the Fe₃O₄ molecule [20, 23]. In addition, this spectrum contains a band with a valley at 1401 cm⁻¹. This band consists of the merging of two absorption peaks, the first one at 1382 cm⁻¹ belongs to the low-energy band of Fe-O in the Fe₃O₄ molecule, and the second peak at 1401 cm⁻¹ belongs to pure maghemite [21]. In addition, the band centered at 1623 cm⁻¹ is from the merging of two absorption peaks. The first one at 1623 cm⁻¹ belongs to yFe₂O₃ [21], and the second peak at 1629 cm⁻¹ is due to the O-H bending [23]. This result confirms the presence of both Fe₃O₄ and γ Fe₂O₃ in the sample of iron nanoparticles. The presence of γ Fe₂O₃ can occur in two ways. The first is that this formula of iron oxide is essentially a defective form mainly presents in the structure of Fe₃O₄ (vacancies in octahedral sides) [24]. Second, the formation of γ Fe₂O₃ can occur when the surface of the Fe₃O₄ layer is exposed to air when preparing the FTIR measurement samples.

Curve b in Figure (7) represents the FTIR spectrum of the CdS nanoparticles. It contains a sharp absorption peak at 618 cm^{-1} , which is due to the tensile vibration of Cd-S [10, 5]. In addition, the peak at 1618 cm^{-1} belongs to the Cd-S vibration [20]. In order to confirm the formation of CdS nanoparticles, curve (b) was compared with the FTIR spectrum of the CdS solid powder of the target material. This comparison showed that the two peaks at 618 cm^{-1} and 1618 cm^{-1} match exactly the spectrum of the CdS powder (not shown).

Curve (c) in Figure (7) shows a relative decay of the peaks at wavenumbers less than 700 cm⁻¹, with the peaks remaining at 618 cm⁻¹ and 463 cm⁻¹, which can be attributed to Cd-S and Fe-O in the Fe₃O₄ molecule. In addition, the curve contains a peak at 812 cm⁻¹, which belongs to Cd-S [5], as well as a peak at 1618 cm⁻¹, which also belongs to Cd-S. The band extending from 1000 cm⁻¹

¹ to about 1185 cm⁻¹ consists of three merged peaks. The first one at 1081 cm⁻¹ belongs to the symmetrical stretching of S=O [20], which indicates the bonding of the sulfur atom in the compound or the formation of Cadmium Sulfite on the surface of the nanoparticles. The other two peaks belong to C-N and C-O, as shown in the figure. The peak at 1382 cm⁻¹ belongs to the low energy region of Fe-O in the Fe3O4 molecule [21]. The peak at 1730 cm⁻¹ is due to the asymmetric stretching of C=O.

In general, the FTIR examinations in Figure (7) confirm the generation of iron particles covered with a layer of iron oxide, as well as the formation of CdS particles. The spectrum in curve (c) confirms the presence of iron particles covered with iron oxide along with CdS particles.

3.3 XRD examination results

XRD measurements of the samples prepared in this work indicate the direct and strong dependence of the crystalline structures on the properties of the liquid in which the laser ablation process was performed. Figure (8) displays the diffraction patterns of all the samples prepared in this work along with their diffraction plans. The broadening of the diffraction patterns of all prepared samples, except for the sample in Figure (8b), indicates very small crystalline grain sizes, which is very common in nanomaterial [25]. This is due to the fact that nanomaterial contains a small number of diffraction planes, which leads to broadening the X-ray diffraction peaks and also leads to a decrease in signal intensity [26]. This can be seen in the samples presented in Figure (8b) are clear due to the relatively large crystalline grains, as confirmed in Figure (4). In addition, some of the peaks are shifted to larger diffraction angles as a result of the contraction of the lattice that occurs due to the large surface area to volume ratio.



Fig. 8. XRD patterns of (a) CdS nanoparticles in Methanol, (b) CdS nanoparticles in water, (c) Fe/CdS nanoparticles in methanol, and (d)) Fe/CdS nanoparticles in water.

996

The diffraction pattern of CdS particles prepared in methanol, Figure (8a), clearly indicates that the particles are formed in two different crystallization phases, namely the hexagonal phase and the cubic phase. The peaks shown in the figure match the two cards JCPDS 41-1049 Hexagonal structure and JCPDS 10-0454 Hawleyite cubic structure. The formation of these two phases in methanol indicates the possibility of forming Homojunction from CdS in nanostructures using laser ablation technique. This result could find several practical applications in the field of using CdS particles in photonics and solar cells.

On the other hand, the CdS particles formed in water using the same temperature conditions and laser parameters, Figure (8b), have a cubic crystalline structure matching the JCPDS 21-0829 card number. This structure is a pure cubic structure devoid of any hexagonal structure. This result agrees well with the result shown in Figure (4), which shows the cubic crystalline structure of the formed particles. In addition, the cubic structure formed in water has a cell parameter ($a = 5.45 \text{ A}^\circ$) that differs slightly from the cell parameter of the particles formed in methanol ($a = 5.818 \text{ A}^\circ$). This phase transformation indicates that despite using the same preparation conditions, the liquid used has a strong influence on the crystallization phase of the cadmium sulfide particles. The peak appearing at $2\theta = 22.93^\circ$ indicates the formation of some impurities on the surface of the nanoparticles or suspended in the liquid, which is most likely Cadmium Sulfite, as indicated in the results of FTIR measurements.

The diffraction patterns in Figures (8c and 8d) indicate another type of effect on the crystalline phase of CdS particles resulting from hybridization. Comparing these two patterns with each other, as well as comparing them with the diffraction patterns in Figures (8a and 8b), shows the significant differences between the crystallization phases of CdS particles depending on the material present in the medium. Figure (8c) indicates the presence of Fe₂O₃, which may be formed by exposing the Fe₃O₄ layer surrounding the particles to air during the preparation of the examination sample, or it may exist mainly as defect points in the formation of the Fe₃O₄ lattice (as confirmed in FTIR previously). It can also be noticed that there are no sharp peaks belonging to CdS other than the peak at $2\theta = 43^{\circ}$. The disappearance of the sharp peaks of CdS and the appearance of a broad band in the region between 15° and 30° suggests the dominance of the random phase of the CdS particles [27]. This randomness can result from the accumulation of a large percentage of material molecules on the surface of nanocrystals, causing irregularity in the crystal lattice [28]. Correlating this result with the diffraction patterns of individual CdS particles in Figure (8a) indicates a very important result, which is that, in PLAL, it is not the liquid used alone that can lead to determining the type of crystallization of the CdS particles but the presence of other materials, even if in a very small percentage. Furthermore, the absence of any peak belonging to iron or Fe₃O₄, although its presence was confirmed by magnetic effects, could indicate the complete coverage of these particles by CdS particles [29].

However, the presence of iron particles, or iron oxide, does not necessarily prevent the crystallization of CdS particles. Figure (8d) indicates another fact, which is that, in PLAL, the presence of iron particles in different media can lead to different effects. By comparing Figures (8b) and (8d), we notice that the presence of iron particles in water has led to a fundamental change in the crystallization phase of the CdS particles. The CdS particles generated in water containing iron particles tended to the completely hexagonal crystallization phase without any peaks indicating the presence of the cubic crystallization phase. This result indicates that the presence of iron particles in the liquid led to the transformation of the crystallization phase of CdS particles from the complete cubic crystal phase to the complete hexagonal phase. In addition, the presence of iron particles prevented the formation of relatively large crystals, in comparison with the case of PLAL in pure water shown in Figure (8b). This result indicates the effect of iron particles on the crystallization phase and crystallization grain size of CdS nanoparticles as well. It is worth mentioning that, all samples shown in Figure (8) do not contain any peaks belonging to CdO. This indicates that cadmium is not oxidized during the laser ablation process.

In general, the results shown in Figure (8) indicate the possibility of forming a Homojunction of CdS with two different crystallization phases, as well as forming a nanostructured Heterojunction of Fe/CdS by controlling the liquid and the materials contained in it. These compositions have special importance in several applications in the field of solar energy

and various photovoltaic and photonics applications. However, the quality of the formation of these compositions requires a detailed study.

4. Conclusion

This work presents the synthesis and characterization of Homophase CdS and Heterophase Fe/CdS nanoparticles prepared by pulsed laser ablation (PLA) in water and methanol using nanosecond pulse duration Nd:YAG laser. Performing PLA in methanol led to the generation of Homophase nanoparticles with mixed hexagonal and cubic crystalline phases of CdS, while the phase was completely transformed to a large scale pure cubic structure when implementing PLA in water. Hetero structures Fe/CdS nanoparticles were obtained successfully in water and methanol. The presence of iron nanoparticles has led to transforming the crystalline state of CdS to dominantly random in methanol and to the pure hexagonal in water. In addition, Fe significantly improved the aggregation properties of the CdS particles in both liquids. The results of this study can have special importance in the field of constructing Hetero and Homo nanostructures and the general use of CdS nanoparticles.

References

[1] A. Kumar, A. Verma, A. Singh, B. C. Yadav, Materials Today: Proceedings 73, 337 (2023); https://doi.org/10.1016/j.matpr.2022.11.047

[2] K. Yang, K. X. Li, C. Yu, D. Zeng, F. Chen, K. Zhang, W. Huang, H. Ji., Chinese Journal of Catalysis 40 (6), 796 (2019); <u>https://doi.org/10.1016/S1872-2067(19)63290-0</u>

[3] J. Zhang, F. Xiao, G. Xiao, B. Liu, New Journal of Chemistry 39 (1), 279 (2015); https://doi.org/10.1039/C4NJ01346H

[4] R. M. Navarro, F. Del Valle, J. L. G. Fierro, International journal of hydrogen energy 33 (16), 4265 (2008); <u>https://doi.org/10.1016/j.ijhydene.2008.05.048</u>

[5] F. Ke, L. Wang, J. Zhu, Nano Research 8, 1834 (2015); https://doi.org/10.1007/s12274-014-0690-x

[6] K. Yang, X. Li, C. Yu, D. Zeng, F. Chen, K. Zhang, W. Huang, H. Ji, Chinese Journal of Catalysis 40 (6), 796 (2019); <u>https://doi.org/10.1016/S1872-2067(19)63290-0</u>

[7] J. Zhou, W. Guo, Nanotechnology 21 (17), 175601 (2010); https://doi.org/10.1088/0957-4484/21/17/175601

[8] Z. A. Kadem, A. B. Sharba, J. M. Jassim, Iraqi Journal of Applied Physics 19 (4C), 257 (2023).

[9] J. Joshy, N. Mishra, V. R. Mehto, A. Banerjee, R. K. Pandey, Journal of Experimental Nanoscience 9 (8), 807 (2014).

[10] A. M. Mansour, R. S. Ibrahim, A. Azab, Journal of Materials Science: Materials in Electronics 33 (13), 10251 (2022); <u>https://doi.org/10.1007/s10854-022-08013-2</u>

[11] T. Cheng, H. Gao, G. Liu, Z. Pu, S. Wang, Z. Yi, X. Wu, H. Yang, Colloids and Surfaces A: Physicochemical and Engineering Aspects 633, 127918 (2022); https://doi.org/10.1016/j.colsurfa.2021.127918

[12] M. Junaid, M. Imran, M. Ikram, M. Naz, M. Aqeel, H. Afzal, H. Majeed, S. Ali, Applied Nanoscience 9, 1593 (2019); <u>https://doi.org/10.1007/s13204-018-0933-3</u>

[13] X. Li, Y. Xi, C. Hu, X. Wang, Materials Research Bulletin 48 (2), 295 (2013); https://doi.org/10.1016/j.materresbull.2012.10.022

[14] L. Meng, J. M. D. Lane, L. Baca, J. Tafoya, T. Ao, B. Stoltzfus, M. Knudson, D. Morgan, K. Austin, C. Park, P. Chow, Y. Xiao, R. Li, Y. Qin, H. Fan, Journal of the American Chemical Society 142 (14), 6505 (2020); <u>https://doi.org/10.1021/jacs.0c01906</u>

[15] A. S. Altowyan, A. M. Mostafa, H. A. Ahmed. Optik 241, 167217 (2021);

https://doi.org/10.1016/j.ijleo.2021.167217

[16] A. Balachandran, S. P. Sreenilayam, K. Madanan, S. Thomas, D. Brabazon, Results in Engineering 16, 100646 (2022); <u>https://doi.org/10.1016/j.rineng.2022.100646</u>

[17] H. A. Majeed, A. B. Sharba, Journal of Physics: Conference Series, 1818 (1), 012131 (2021); <u>https://doi.org/10.1088/1742-6596/1818/1/012131</u>

[18] T. Fromme, L. K. Tintrop, S. Reichenberger, T. C. Schmidt, S. Barcikowski, ChemPhysChem 24 (11), e202300089 (2023); https://doi.org/10.1002/cphc.202300089

[19] M. H. Mahdieh, B. Fattahi, Applied Surface Science 329, 47 (2015); https://doi.org/10.1016/j.apsusc.2014.12.069

[20] N. Zhang, X. Li, Y. Wang, B. Zhu, B., J. Yang, Ceramics International 46 (13), 20974 (2020); <u>https://doi.org/10.1016/j.ceramint.2020.05.158</u>

[21] A. Bahari, Journal of Superconductivity and Novel Magnetism 30, 2165 (2017); https://doi.org/10.1007/s10948-017-4014-8

[22] F. D. D. Irianti, H. Sutanto, P. Priyono, A. A. Wibowo, A. N. Syahida, I. Alkian, Journal of Physics: Conference Series 1943 (1), 012014 (2021); https://doi.org/10.1088/1742-6596/1943/1/012014

[23] L. Nalbandian, E. Patrikiadou, V. Zaspalis, A. Patrikidou, E. Hatzidaki, C. N Papandreou, Current Nanoscience 12 (4), 455 (2016);

https://doi.org/10.2174/1573413712666151210230002

[24] K. Kwon, B. H. Lee, M. Shim, Chemistry of materials 18 (26) 6357 (2006); https://doi.org/10.1021/cm0621390

[25] S. Kumar, J. K. Sharma, Materials Science-Poland 34 (2), 368 (2016); https://doi.org/10.1515/msp-2016-0033

[26] R. Seoudi, S. H. A. Allehyani, D. A. Said, A. R. Lashin, A. Abouelsayed, Journal of Electronic Materials 44, 3367 (2015); <u>https://doi.org/10.1007/s11664-015-3838-x</u>

[27] E. M. Semenova, S. A. Vorobyova, A. I. Lesnikovich, Optical Materials 34 (1), 99 (2011); https://doi.org/10.1016/j.optmat.2011.07.008

[28] G. G. Yordanov, E. Adachi, C. D. Dushkin, Colloids and Surfaces A: Physicochemical and Engineering Aspects 289 (1-3), 118 (2006); <u>https://doi.org/10.1016/j.colsurfa.2006.04.019</u>

[29] A. Samadi-Maybodi, M. R. Shariati, A. H. Colagar, ChemPlusChem 83 (8), 769 (2018); https://doi.org/10.1002/cplu.201800315