

Atmospheric Plasma Jet-Assisted Synthesis of CuO Nanofluids: Insights into Structural and Optical Properties

Ghada Sabah Mahdi^{1,a)}, Aseel Mustafa Abdul Majeed^{1,b)}, Randa Kamel Husain^{1,c)}

¹*Department of Physics, College of Science, Mustansiriyah University, Baghdad, Iraq.*

^{a)} *ghada1997@uomustansiriyah.edu.iq*

^{b)} *Corresponding Author: aseelalaziz@uomustansiriyah.edu.iq*

^{c)} *dr.randa.kamel@uomustansiriyah.edu.iq*

Abstract. This study presents the fabrication of CuO nanoparticles through the use of atmospheric plasma jet technology. The prepared synthesized CuO nanoparticles were analyzed by multiple characterization analyzations, like X-ray diffraction (XRD), scanning electron microscopy, energy-dispersive X-ray spectroscopy (EDS) moreover UV-Vis spectroscopy. XRD results showed the absence of additional peaks associated with secondary phases, confirming the high purity of the CuO nanoparticles. Besides, the CuO NPs synthesized with high purity that assured by EDX analysis. SEM analysis was used to examine the surface morphology, revealing a high degree of nanoparticle agglomeration. The energy bandgap was 4 eV for CuO Nanoparticles. The current–voltage analysis indicated that the solar cell achieved a power conversion efficiency of 0.031%, with a fill factor of 18.46%.

Keywords: Plasma jets, CuO nanoparticles, Structural and Optical properties, solar cell

INTRODUCTION

Metal oxide semiconductors have a significant attention in optical applications as a reason of their ease of use, easy synthesis, safety, and acceptable cost. Copper oxide (of chemical formula CuO) is a p-type semiconductor with has band gap in range 1.3 – 1.5 eV. [1-2], which enables copper oxide to absorb light in a wide range of spectra, especially in the visible light range. Nano-copper oxide (CuO) has optical and absorption properties that make it an important material in optical and electronic applications. It has a high absorption coefficient in the visible and ultraviolet light ranges, making it suitable for solar applications [3]. Due to its high light absorption, which makes it effective in converting light into heat energy. Copper oxide nanomaterials possess unique optical properties due to their nanoscale size, exhibiting optical behavior that differs from conventional materials. They feature strong light absorption in the visible region and a narrow bandgap, making them effective in applications such as solar cells [4-7], optical sensing [8], and photocatalysis [9]. They also exhibit color variations depending on particle size and their surrounding environment due to quantum effects.

The preparation methods of nanocrystalline copper oxide significantly influence its structural properties, such as crystal size, shape, and particle size distribution, which directly impact its optical properties [10-11]. For example, preparation by microwave irradiation precipitation can produce smaller giving higher effectivity in antimicrobials [12], it is highly effective in bactericidal activities and has great inhibition potential [13]. Copper oxide (CuO) nanoparticles were prepared using various methods, including spray decomposition [14], electrochemical techniques [15], hydrothermal treatment [16], and wet chemical methods [17]. The study demonstrated that optical properties, such as the energy band gap, depend on the preparation method. For example, CuO nanoparticles prepared by sonochemical methods [18], the distribution of CuO NPs is obtained in the range between 35 - 125 nm and a big direct energy band gap (3.85 eV). On the other hand, the preparation conditions controlled the properties of the created nanoparticles [19]; the particle sizes increased according to the precursor concentration. In the co-precipitation preparation of CuO method, it revealed the effect of sodium hydroxide concentration on structural properties; particle size, degree of crystal distortion, and optical gap which lies in range 1.47 and 1.39 eV.[20]. Recently, CuO nanoparticles were introduced by non-thermal plasma technique [21]. Plasma lay out notable features in contrast with other nanoparticle preparation technologies, due to easy operation and maintain, fast - time processing time, and zero - waste or hazardous compounds [22]. Therefore, understanding the relationship between the synthetic method and optical properties is important for improving material performance in optical and photonic applications. This research aims to prepare copper oxide nanoparticles using plasm-assistant method. Studying the influence of the preparation

method on the structural characteristics of the synthesized particles and their relationship with the optical properties to achieve optimal conditions for fabricating the solar cell heterojunction.

METHODS AND MATERIALS

Nanoparticles of Copper oxide were prepared by plasma - jet system, (see Figure 1). The setup utilized a high-voltage DC power supply (20 kV) and employed a stainless-steel tube as the cathode. A (0.98 g) weight of hydrated copper nitrate salt $[\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}]$ salt is dissolved in deionized water under magnetic stirring to obtain 0.2 M solution. High-purity argon gas (99.99%) was employed as the discharge medium, and its flow rate was maintained at 2 L/min using a flowmeter for precise control. The plasma jet extended through the air, with the nozzle positioned about 2 cm above the salt solution's surface. The salt solution remains in presence of plasma processing for a duration of 5 minutes. A noticeable color change at the beginning of the process suggested the formation of CuO nanomaterials. UV-Vis absorption spectra of the samples, ranging from 200 to 900 nm, were recorded using a Metertech dual-beam UV-Vis-NIR spectrometer. The synthesized CuO nanoparticles were analyzed by many techniques like XDR, EDS and SEM. The copper oxide nanoparticle solution was drop-cast onto a silicon substrate and then dried in an electric convection oven at 250 °C. One side of the silicon slide was polished, cleaned with distilled water, and thoroughly dried before being placed in the oven. The drop-casting process involved applying seven drops at three-minute intervals. These nanoparticles are intended for future use in solar cell applications.

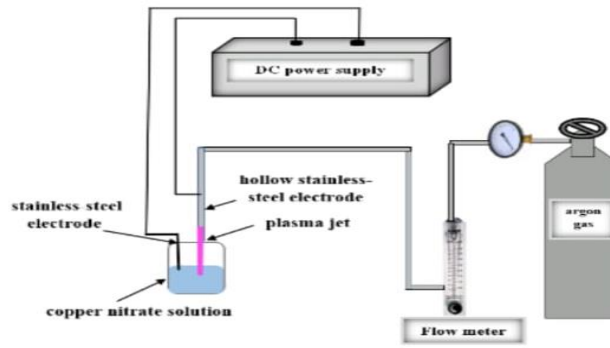


Fig.1: Plasma jet system

RESULTS AND DISCUSSION

XRD analyses

X-ray diffraction (XRD) analysis confirmed the crystalline structural nature and its phase purity of CuO nanoparticles synthesized using the plasma jet (APJ) method. As reported in previous studies, the XRD pattern of CuO nanoparticles was obtained over a 2θ range of 15° to 85°, as illustrated in the figure (2). The diffraction peaks observed at 35.64° and 38.84° are characteristic of CuO and correspond to the (11-1) and (111) crystallographic planes, respectively. The Debye-Scherrer equation was adopted to calculate the crystallite size of the CuO nanoparticles, as given in Equation (1) [23,24].

$$D(A^\circ) = \frac{K\lambda}{\beta \cos \theta} \quad (1)$$

In this equation, D remarked to the crystallite size, k is Scherrer's constant (typically valued at 0.9), while, the wavelength of X-ray wavelength is represented by λ denotes the (1.540 Å), the symbol of β stands for the full width at half maximum (FWHM) of the diffraction peaks measured at the Bragg angle θ . The Copper oxide nanoparticles were formed in a crystallite, its an average size was 14nm.

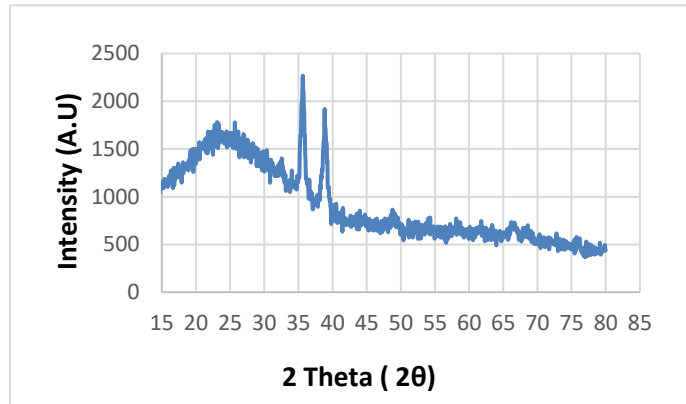


Fig. 2: XRD pattern for CuO NP synthesis by plasma jet

SEM analysis

Scanning electron microscopy was used for inspect the surface morphology of CuO nanoparticles produced via the plasma jet method. The SEM images revealed that the synthesized particles exhibited nanoscale features and morphology, with noticeable agglomeration, indicating that full dispersion of the nanoparticles was not attained. The shapes of the CuO NPs synthesized by plasma jets had the appearance of a spindle shape like, as shown in Fig. 3. The appearance of larger grains and nanoparticle aggregation is likely due to the high surface area and elevated surface energy characteristic of the CuO nanoparticles [25]. As a reason of their high surface area-to-volume ratio, the nanoparticles tended to stick together or form agglomerates as a result of attractive physical interactions [26].

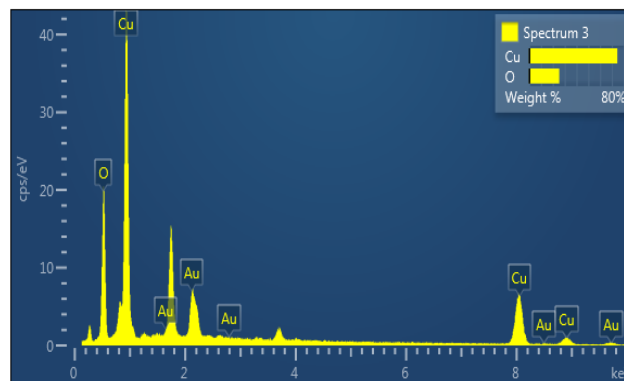


Fig. 3: SEM images of CuO NPs synthesized by by plasma jet

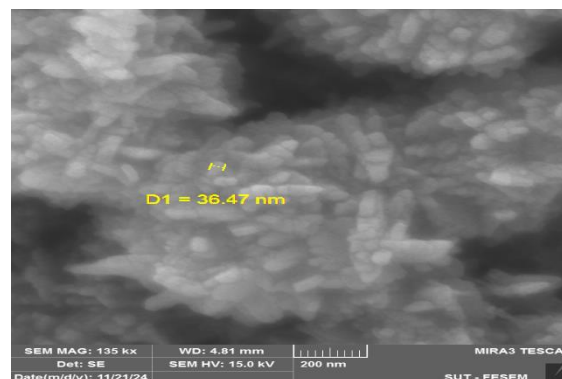


Fig. 4: EDX spectra of the CuO nanoparticles synthesized the plasma jet technique

To identify the chemical composition of the fabricated specimen, the energy-dispersive X-ray (EDX) technique was conducted. Fig.4 illustrates the EDX spectrum, confirming the existence of copper (Cu) and oxygen

(O) elements within the CuO nanoparticles. EDX analysis confirmed that the CuO nanoparticles were compositionally pure, with no detectable traces of foreign elements or impurities. The achieved production of CuO nanoparticles using a plasma jet method was supported with EDX spectral analysis, which aligned with the findings obtained from XRD measurements [27].

Optical properties

CuO nanoparticles were produced using the Atmospheric Plasma Jet technique, and their optical characteristics were examined through UV-Vis spectroscopy. The results showed a decline in absorption as the wavelength increased. This reduction in absorption could be due to factors such as internal electric fields within the crystal structure and possible lattice deformations. It was noted that the absorption edge of the CuO nanoparticles shifted toward shorter wavelengths in comparison to bulk CuO. This blue shift is likely a result of enhanced quantum confinement reactions due to the reduced particle size of the CuO nanoparticles. The band gap was calculated directly from the cut-off wavelength using Planck's law, as illustrated in the equation below [28,29].

$$E_g = \frac{hc}{\lambda_{cut}} = \frac{1240}{\lambda_{cut}} \quad (2)$$

In this context, E_g represents the optical energy gap, h ($6.626 \times 10^{-34} \text{ J}\cdot\text{s}$) is Planck's constant, c ($3 \times 10^8 \text{ m/s}$) is the speed of light, and λ_{cut} is the cut-off wavelength associated with the optical band gap. The value of λ_{cut} was obtained graphically by extrapolating the linear section of the absorption spectra." UV-Vis absorption curve of CuO NPs as a function of wavelength are shown in Fig. 5. The optical absorption spectra curve shows a shift towards the blue region of the absorption, which can be assigned to the decrease in particle size [30].

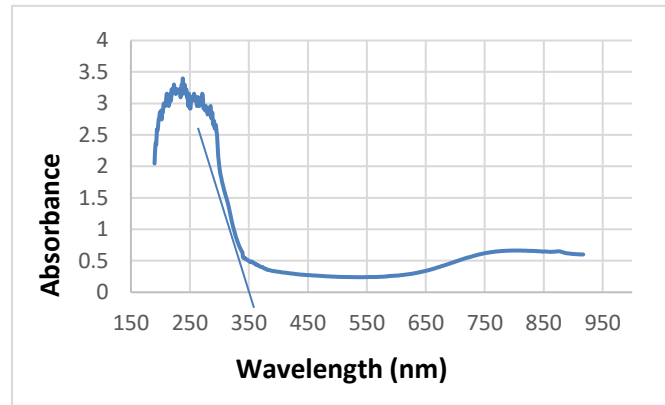


Fig. 5: CuO nanoparticles optical absorption spectra

"Using the absorbance spectra, the absorption coefficient of CuO nanoparticles was estimated through a graphical approach based on Tauc's relation for direct electronic transitions, as illustrated in the corresponding equation (3) [27].

$$(\alpha h\nu)^r = A(h\nu - E_g) \quad (3)$$

In this equation, α represents the absorption coefficient, h is Planck's constant, ν denotes the frequency of the incident photons, and A is a constant (typically taken as 0.9). E_g stands for the optical band gap, while r is a factor reflects the kind of electronic transition in this case, $r = 2$ corresponds to an allowed direct transition. To determine the band gap, a charting of $(\alpha h\nu)^2$ against photon energy ($h\nu$) is used, and the value of E_g is obtained by extending the linear region of the curve to where it intersects the energy axis. as illustrated in Fig. (6). The value of optical band gap for CuO NPs was found ($E_g = 3.9 \text{ eV}$). That is the same result obtained by [18]. The E_g of the copper oxide nanoparticles was achieved bigger in the reported literature. An enlargement of the energy gap between the conduction and valence bands in CuO nanoparticles can be linked to their reduced crystal size.

Copper oxide nanoparticles (CuO NPs) were deposited onto the silicon surface using the drop-casting technique to fabricate an Al/ p-CuO /p-Si/Al solar cell. The I-V characteristics showed that the forward bias current was significantly higher than the reverse bias current, as illustrated in the measurements. At forward bias voltages below 4 V, the current primarily results from electron-hole pair recombination. When the applied voltage exceeds this

threshold, electrons gain sufficient energy to overcome the potential barrier of the junction. “This type of current is referred to as diffusion current. Figure 8b presents the reverse I–V characteristics, along with the device parameters measured under dark conditions and illumination at a light intensity of 100 mW/m². Under illumination, the reverse current of the Al/p-Si/p-CuO/Al heterojunction increases compared to its value in the dark, indicating that photo-generated charge carriers contribute to the overall photocurrent through electron–hole pair generation [31, 32]. This response highlights the role of incident photons in creating charge carriers within the device.

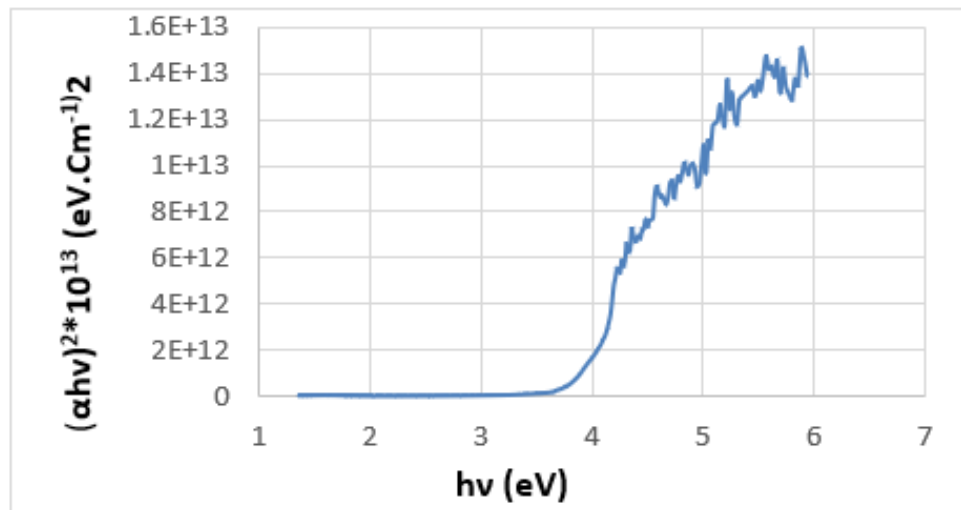


Fig. 6: Optical bandgap energy for CuO NPs.

Figure 9 presents the measurements of open-circuit voltage, short-circuit current, fill factor, and efficiency under an illumination intensity of 100 mW/m². The I–V curve shown also illustrates the device behavior under varying load resistance in a light-exposed environment. This experiment provides a straightforward method for evaluating solar cell efficiency. One key parameter is the short-circuit current, which occurs when the external resistance is zero and the voltage across the cell is also zero. The open-circuit voltage is observed when the external resistance is very high, resulting in zero current flow. By identifying these two key points—VOC and ISC—the maximum power point can be estimated.

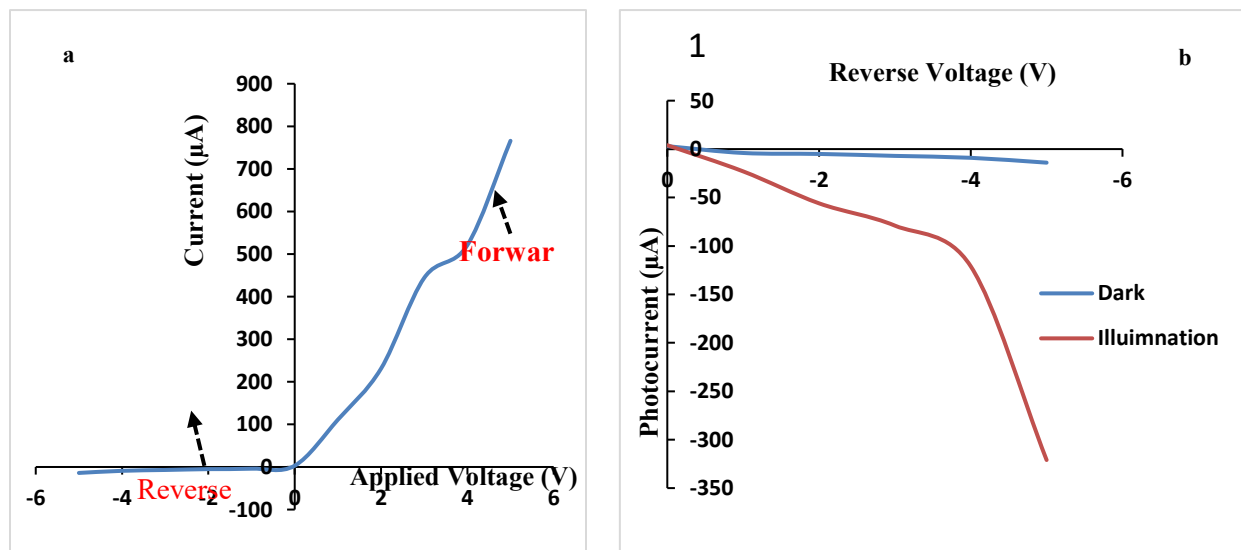


Fig. 8. (a) I–V dark characteristics of CuO NPs in forward and reverse direction, (b) I–V characteristics of CuO NPs in Dark and illumination

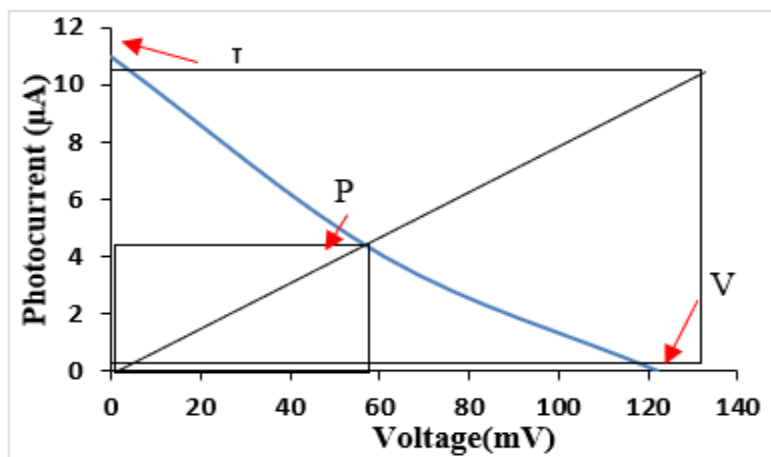


Fig. 9. Open-circuit voltage of the (Al/p-Si/p-CuO) heterojunction.

CONCLUSION

CuO nanoparticles were effectively synthesized using the plasma jet method. Based on XRD and EDS analyses, the resulting nanoparticles demonstrated high purity. The crystalline structure of the CuO nanoparticles has been confirmed by the technique of XRD, with an estimated average crystallite size of approximately 14 nm. Scanning electron microscopy (SEM) technique assists the synthesized CuO nanoparticles in forming aggregates containing little particles, owing an average diameter in approximately 36 nm. The solar cell demonstrated an efficiency of 0.031%.

ACKNOWLEDGEMENTS

This study is supported by Plasma Physics Lab., Physics Department, College of Science, Mustansiriyah University

REFERENCES

1. Zehra Nur Ozer, Mehmet Ozkan, and Suat Pat, Optical and electric characteristics of CuO nanoparticle-doped ZnO thin films using thermionic vacuum arc deposition system, *J Mater Sci: Mater Electron*, 35:456, (2024).
2. Ohya Y, Ito S, Ban T and Takahashi Y.2000.Preparation of CuO thin films and their electrical conductivity, *Eng. Mater* 181:113- 116.
3. Ahed M. Al-Fa'ouri, Omar A. Lafi , Husam H. Abu-Safe , and Mahmoud Abu-Kharma, Investigation of optical and electrical properties of copper oxide - polyvinyl alcohol nanocomposites for solar cell applications, *Arabian Journal of Chemistry*, Volume 16, Issue 4, (2023).
4. Mossa Umran, N., Mustafa Abdul Majeed, A., Subhi Sultan, Z., Examination the properties of doped copper oxide by silver: Prepared chemical method, *Journal of Physics: Conference SeriesOpen Access*Volume 1279, Issue 131 July (2019).
5. Ismail, R.A., Ramadhan, I., Mustafa, A., Growth and characterization of Cu₂O films made by rapid thermal oxidation technique, *Chinese Physics Letters*Volume 22, Issue 11, Pages 2977 - 29791 November(2005).
6. Ali Hameed Rasheed, Anfal Ismael Ibrahim , Suraa Reaad , Mustafa M. Kadhim, Synthesis and Characterization of CuO Nanoparticles For Increase The Efficiency of the photovoltaic cell, *Egypt. J. Chem.* Vol. 66, No. 1 pp. 49 - 53 (2023).
7. Aseel Mustafa Abdul Majeed, Asmaa Deiaa Nusseif, Nibras Salah Hamed, Investigations of ZnO-NiO/Psi heterojunction for solar cell application, *AIP Conference Proceedings*, 2144, 030015 ,(2019).
8. B. Renganathan , C.K. Gopakumar , A.Kalai Priya , SubhaKrishna Rao, et al., Optimizing Gas Sensing Performance of CuO Nanoparticles via Sol-Gel Synthesis Approach for Efficient Detection of Ammonia Gas, *Materials Research Bulletin* Volume 170, 112556, February (2024).
9. Hridoy Saha , Ankita Dastider , et al., Photocatalytic performance of CuO NPs: An experimental approach for process parameter optimization for Rh B dye, *Results in Materials*, Volume 24,100614, , December (2024).

10. Khuram Ali, Muhammad Sajid ,Suriani AbuBakar, Ayesha Younus , Hassan Ali , Muhammad Zahid Rashid, Synthesis of copper oxide (CuO) via coprecipitation method: Tailoring structural and optical properties of CuO nanoparticles for optoelectronic device applications, *Hybrid Advances*, Volume 6, August (2024).
11. Oleksii Diachenko, Jaroslav Kováč, Jr. , Oleksandr Dobrozhan , Patrik Novák , Jaroslav Kováč , Jaroslava Skriniarova and Anatoliy Opanasyuk, Structural and Optical Properties of CuO Thin Films Synthesized Using Spray Pyrolysis Method, *Coatings* 2021, 11, 1392(2021).
12. Ghdeeb,N.J, Mohammed, A.H, Majeed, A.M.A, The Anti-proliferative Activity of Factory Wastes Nanoparticles against Uterus Cancer cells: In-vitro Study, *Nano Biomedicine and Engineering*, 14(2), pp.149-158, (2002).
13. Hussain, R.K., Aziz, W.J., Ibrahim, .Antibacterial activity of CuO - cellulose nano rods depends on anew green synthesis (cotton), *Journal of Nanostructures*, 9(4), pp. 761–767,(2019).
14. C. Salame, P. Mialhe, and J.-P. Charles, “VDMOSFET model parameter extraction based on electrical and optical measurements,” *Microelectron. J.* 32, 599–603 (2001).
15. Rishu Katwal, Harpreet Kaur, Gaurav Sharma, Mu. Naushad and Deepak Pathania, Electrochemical synthesized copper oxide nanoparticles for enhanced photocatalytic and antimicrobial activity, *Journal of Industrial and Engineering Chemistry*, Volume 31, 25, Pages 173-184, November (2015).
16. Safana Alzalzala and Amer M. J. AL-Shamari, Preparation and Characterization of Copper Oxide CuO (II) nanoparticles Prepared by a Hydrothermal Method and for Solar Cells applications, *Journal of Kufa-Physics*, Vol. 15 No. 02 (2023).
17. Zubin Parekh, Sunil Chaki, Anilkumar B Hirpara, Gauravkumar H. Patel, Rohitkumar Kannaujiya, Ankurkumar J Khiman,i M. P. Deshpande, CuO nanoparticles – Synthesis by wet precipitation technique and its characterization, *Physica B Condensed Matter* 610(2–3):412950 (2021).
18. Mohammed J. Mohammed Ali a, Munthir Mohammed Radhy b, Salam Jumah mashkoor c , Ehab M. Ali b, Synthesis and characterization of copper oxide nanoparticles and their application for solar cell, *Materials Today: Proceedings*, Accepted 10 October (2021).†
19. Sttar, M.A.K.A., Mkhaiber, A.F., Majeed, A.M.A., Study of the effect of using nanomaterial in radiological shielding, *Aip Conference proceedings*, (2019), 2190, 020077.
20. Abdulateef, A.N., Alsudani, A., Chillab, R.K., Jasim, K.A., Shaban, A.H., *Journal of Green Engineering*, 2020, 10(9), pp. 5487–5503.
21. Tabarak F. Orabil · Kadhim A. Aadim1, Study of the structural and optical properties of copper oxide nanoparticles prepared by plasma jet and their application as solar cells, *Journal of Optics*, 30 july (2024).
22. Bahaa Hassoun Abbas, Nisreen Kh Abdalameer, Raghad S. Mohammed, Synthesis of Copper Oxide Nanostructures by Ar Plasma Jet and Study of Their Structural and Optical Properties, *Iraqi Journal of Science*, Vol. 65, No.4, pp: 1999-2006, (2024).
23. Raghad S. Mohammed, Kadhim A. Aadim, and Khalid A. Ahmed, Synthesis of CuO/ZnO and MgO/ZnO Core/Shell Nanoparticles with Plasma Jets and Study of their Structural and Optical Properties, *Journal of Modern Science: Vol. 8 : Iss. 2*(2022).
24. Hussein, I.F., Nusseif, A.D., Majeed, A.M.A., Analytical study of ZnO:NiO nanocomposite of antibacterial activities, *Plant Archives* Volume 20, Issue 1, Pages 2747 – 2750, (2020).
25. Ghdeeb, N.J., Abdul Majeed, A.M., Mohammed, A.H., Antibacterial activity and physical properties of some metal oxide nanoparticles prepared by different methods, *AIP Conference Proceedings*, 2834(1), 090004, (2023).
26. Nadia Jasim Ghdeeb, Aseel Mustafa AbdulMajeed, Asma Hadi Mohammed, Role of Extracted Nano-metal Oxides from Factory Wastes in Medical Applications, *Iraqi Journal of Science*, vol.64, No. 4, PP. 1704-1716, (2023).
27. Jasim, K.A., *Journal of Superconductivity and Novel Magnetism*, 2013, 26(3), pp. 549–552.
28. N. Khlifi , C. Zerrouki , N. Fourati , H. Guermazi , S. Guermazi , Investigation of structural and optical properties of TM-doped CuO NPs: Correlation with their photocatalytic efficiency in sunlight-induced pollutant degradation, *Measurement*, Volume 237, 115209, 30 September(2024).
29. Rasha S Ahmed, Raghad S Mohammed, Aseel Mustafa Abdul Majeed and Allwin Sudhakaran, Biological activity of MgO nanoparticle synthesis by plasma-assisted reduction method, *Physica Scripta*, 99, 115901, (2024).
30. Aseel Mustafa Abdul Majeed, Itab F. Hussein, Rana O. Abd-Jalil, Fabrication of High Responsivity for MgO NPs/PSi Heterojunction Device by Sol-Gel Technique, *Silicon*, 12(5), pp. 1007–1010, (2020).
31. Ahmed, B.A., Mohammed, J.S., Fadhil, R.N., ...Shaban, A.H., Al Dulaimi, A.H., *Chalcogenide Letters*, 2022, 19(4), pp. 301–308
32. Raid A. Ismail, Aseel Mustafa Abdul, Preparation and investigation of nanostructured SnO₂: Pd/ porous silicon/c-Si heterostructure solar cell, *Journal of Solid-State Electrochemistry*, 25(3), pp. 1039–1048, (2021).