Vol.4 Iss.2 pp.47-57 International Journal of Renewable Energy and Sustainability (RES)

Deposition and Photo-Electrochemical Investigation of n-Type Cu_2O Nanolayers for Effective Solar Energy Conversion Assessment

Kahina Aoudia#1, Naima Brinis[1], Houa Hammache[1], Hassiba Tighidet[1], and Nabila Cherchour[1]

[1]*Université de Bejaia, Faculté de Technologie, Laboratoire d'Electrochimie,*
Corrosion et de Valorisation Energétique, 06000 Bejaia, Algérie

#Kahina.aoudia@univ-bejaia.dz
Naima.brinis@univ-bejaia.dz
Houa.hammache@univ-bejaia.dz
Hassiba Tighidet@univ-bejaia.dz
Nabila.cherchour@univ-bejaia.dz

***Abstract*— Copper oxide (Cu_2O), a p-type semiconductor with a bandgap of approximately 2 eV, is particularly suitable for solar cell applications. However, the inability to reverse its intrinsic behavior makes it difficult to produce n-type Cu_2O, which is required to construct p-n junctions. This study focuses on optimizing the électrodeposition process for creating n-type Cu_2O thin films. Stable n-Cu_2O films have been synthesized by controlling parameters such as temperature, potential applied, pH, and deposition time. A cubic polycrystalline structure was shown by X-ray diffraction analysis (XRD), while electrochemical impedance spectroscopy (EIS) demonstrated an efficient charge transport. The main goal is to investigate how deposit parameters affect photochemical properties in order to maximize p-n junction formation and enhance solar cell efficiency. These findings pave the way for the development of more affordable and long-lasting photovoltaic technology.**

***Keywords*— Electrodeposition, Thin films, Copper oxide, Semiconductor, solar cell.**

I. INTRODUCTION

With the rise of solar energy, researchers have turned to alternative materials to improve the efficiency of solar cells. The choice of materials lies in their ability to determine the efficiency, durability and cost of these devices. The materials used in the manufacture of solar cells affect their ability to convert sunlight into electricity efficiently. Material characteristics such as conductivity, durability and cost are key factors in their use in solar cells [1-2].

Copper oxides have emerged as a promising option due to their unique properties and potential to enhance solar energy capture. Cu_2O thin films offer unique properties such as conductivity, transparency, corrosion resistance and catalysis. Cu_2O is an attractive semiconductor material for low-cost solar energy applications [3-4] due to its non-toxicity, low cost, direct band gap of 2 eV at room temperature, and high absorption coefficient in the visible region [5]. Their thickness varies from a few nanometers to a few micrometers, making them particularly interesting for many applications. Copper oxide, Cu_2O, is of significant importance in the research of semiconductor materials for photovoltaics by virtue of its peculiar electronic properties. Not only does it pose an intermediate band in the energy gap, but it also has the exceptional property of being an insulating oxide host or a hole conductor, p-type semiconductor, by copper ion vacancies [6-7].

The importance of thin-film deposition methods lies in their ability to precisely control the thickness, composition, microstructure and properties of thin films, which has a direct influence on their performance and applications. To prepare Cu_2O thin films, a number of techniques have been used, such as chemical vapor deposition, chemical oxidation, thermal oxidation [8] reactive sputtering, sol gel [9], and electrodeposition [10-11]. Since it is easy to use and can be used to create thin films with a lot of surface area, the electrodeposition method is one of these deposition processes that is appealing [12-13].

Copper oxide (Cu_2O) films obtained by electrodeposition are generally p-type semiconductors, due to the intrinsic nature of Cu_2O, which, when deposited on a substrate from solutions containing Cu^{2+} ions, forms a material where electron vacancies (holes) are the majority charge carriers, typical of a p-type semiconductor [14-15].

However, to obtain n-type Cu_2O films, it is necessary to modify the deposition conditions by playing on the electrochemical parameters during

ISSN: 2961-6603

the electrodeposition process. In this way, we can promote the formation of electrons as the majority charge carriers and thus obtain an n-type material, necessary for the realization of a p-n homojunction in photovoltaic devices [16].

This study investigates the effects of the deposit parameters, such as temperature, tension and pH, on the photochemical characteristics of Cu_2O films made by cathodic électrodeposition on a stainless steel substrate. The knowledge gained will help to optimize the manufacturing process to enhance the performance of energy conversion devices.

II. EXPERIMENTAL

Cu_2O thin films were electrodeposited on stainless steel substrates with an active surface area of 4 cm^2 using a three-electrode electrochemical cell containing an aqueous solution of sodium acetate (CH_3COONa) and copper acetate ($(CH_3COO)_2Cu$) at different pH. Sodium acetate was added to the solution to promote complex formation, slowly releasing copper ions into the medium allowing uniform growth of Cu_2O thin films. While copper acetate was used as a source of Cu^{2+}. The reference electrode was a saturated calomel electrode (SCE) and the counter electrode was a platinum grid. Before each deposition process, the substrates were well polished with abrasive paper and cleaned with distilled water, in order to facilitate Cu_2O nucleation and remove surface contamination. The electrodeposition was performed in Potentiostatic mode using a PGP 201 Potentiostat/Galvanostat, connected to a computer allowing data acquisition with the voltamaster 1 software. Photocurrent characterization was performed in a three-electrode photoelectrochemical cell with a 200 W tungsten lamp illuminating the working electrode, the light being turned on and off manually at zero bias voltage. Electrochemical impedance measurements were performed using an Autolab in a solution containing 0.5 M sodium sulfate (Na_2SO_4). Structural characterization of the films was done by X-ray diffraction (XRD) (Empyrean serie 03 Malvern Panalytical)) in the 2θ range (5°- 100°).

A. *Effect of temperature*

Temperature has effects that influence both the kinetics of electrochemical reactions and the properties of deposits, and is therefore a crucial factor in the electrochemical deposition of oxides. However, the influence of temperature on the morphology, crystalline structure, optical and electrochemical properties of copper oxide films formed by electrodeposition has been studied. For this purpose, we performed a voltammetric study in acetate solution at temperatures ranging from T = 40 to 80°C. The fig. 1 shows the voltamograms obtained.

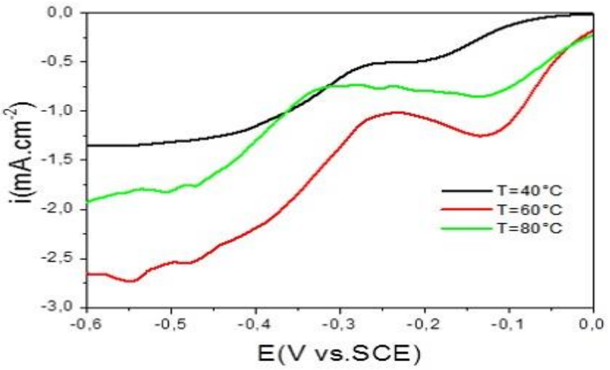

Fig. 1: Linear voltamograms obtained on a stainless steel electrode for a solution of $(CH_3COO)_2Cu$ at 0.01M and (CH_3COONa) at 0.2 M, pH = 6.5, Temperatures T= 40,60 and 80°C.

According to this figure, the formation of a cathodic peak is observed between E = -0.1 V vs. SCE and E = -0.2 V vs. SCE for all temperatures. This peak is attributed to the reduction of Cu (II) to Cu (I) with the formation of Cu_2O (Eq.1) [17]:

$$2Cu^{2+} + H_2O + 2\acute{e} \longrightarrow Cu_2O + 2H^+ \qquad (1)$$

At 40°C, the curve might show less distinct or weaker peaks, involving slow kinetics and potentially an amorphous or rough deposit.

The slow progression and the tendency to form irregular or shapeless deposits indicate a deposition process that is less efficient, potentially due to limited ionic mobility or delayed surface reactions, resulting in indistinct deposits. These cases are also promote to the presence of structural defects such as a low level of crystallinity or non-uniform grain growth, which affect the material's properties, such as electrical conductivity and mechanical strength [18]. At 60 °C, appeared to be optimal, with intense and well-defined current peaks, indicating rapid dynamics and compact, perfectly crystallized, and homogeneous deposits that promote adhesion and reduce defects [19]. However, at 80 °C, although increased kinetics are expected, the reduction in peak intensity suggests possible limitations, such as insufficient diffusion or undesirable morphological changes that decrease the deposition efficiency and amplify structural defects.

B. *Effect of potential*

Determining the morphology, crystal structure, and properties of the deposited films depends on the effect of the applied potential on the electrodeposition of copper oxides, especially Cu_2O. Indeed, the effect of the deposition potential on Cu_2O films is governed by multiple factors that influence the reaction kinetics, morphology, chemical composition, and functional properties of the prepared films. An optimal deposition potential enables the fabrication of high-quality films that are both well-crystallized and efficient, whereas potentials that are too high or too low can lead to defects or difficulties in film growth.

In order to investigate the effect of applied potential on the photoactivity of formed semi-conductors, we looked at the photo-courant response of Cu_2O films deposited at various cathodic potential values: -120, -150, and -200 mV vs. SCE under T = 60°C, pH= 6.5 and t = 60min (fig.2).

We notice that all the samples present curves of the same shape. When the films are illuminated, they generate an anodic current, i.e., the depletion region is positively charged, so that under illumination, holes move to the electrolyte and electrons move to the semiconducting layer [17], which clearly indicates that all these structures have n-type conductivity. We can also see that when the deposition potential is -150 mV vs. SCE, the current density value becomes more intense (-380 μA/cm²) compared to the other nanostructures grown at -120 and -200 mV vs. SCE indicating thus, that a better photoresponse for this deposition is obtained at -150 mV vs. SCE.

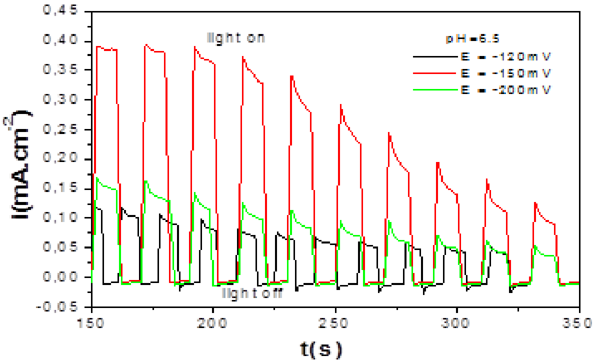

Fig.2 Photo current measurements of copper oxide films deposited at diverse potentials (E = -120, -150, -200 mV vs. SCE).

This result indicates that the deposition potential has a direct impact on the performance of copper oxide films, particularly on the photocurrent response. An optimal potential of -150 mV vs. SCE promotes the formation of highly crystalline films with a homogeneous morphology and low defect density, which enhances charge separation and minimizes recombination, leading to a high photocurrent. However, a too high potential can cause disordered growth, creating structural defects that act as recombination centers and reduce the photocurrent. Similarly, an insufficient potential results in incomplete or poorly crystallized films, limiting light absorption and carrier generation, thereby reducing the photoelectrical current [20].

C. Effect of deposition time

Deposition time is an important factor in improving the performance of Cu_2O-based solar cells. A deposition time that is too short or too long can result in a lack of light absorption, increased carrier recombination, or a poor-quality crystal structure. An optimum deposition time is therefore necessary to promote optimum thickness, morphology and crystalline quality to increase conversion efficiency. In order to find the optimal time for the deposition of Cu_2O thin films, a series of Cu_2O deposits were prepared from a solution at pH = 6.5, T = 60°C and E = -150mV vs. SCE at different values of applied time t = 15, 30, 45 and 60 min. Fig. 3 shows the photographic images obtained for the electrodeposited thin films at different times.

Fig.3 Cu_2O thin films deposited at different time values.

We noticed that the surface of the electrode is uniformly covered with a brown oxide layer. We also observed that there is a color change from light brown to dark brown when the deposition time increases from 15 to 60min. This indicates an increase in the thickness of the deposited Cu_2O thin films with increasing deposition time, which may influence the quality of the films formed. An ideal deposition time of 60 minutes is crucial to ensure the quality of electrodeposited Cu_2O films. This time allows for an optimal thickness that maximizes light absorption while minimizing charge carrier recombination. It also promotes a well-ordered crystalline structure and a balanced surface morphology, which enhances light absorption and charge separation. Consequently, this deposition time improves the photoelectric efficiency of Cu_2O films [21].

In view of confirming these observations, we performed photo-current measurements for Cu_2O films prepared at different deposition times (t = 15, 30, 45 and 60 min) and the results obtained are shown in Fig.4. We noticed from these results that the increase of the deposition time generates an increase of the current density and that the value of the photo response obtained for the Cu_2O layer deposited during 60 min is better compared to those deposited during 15, 30 and 45 min.

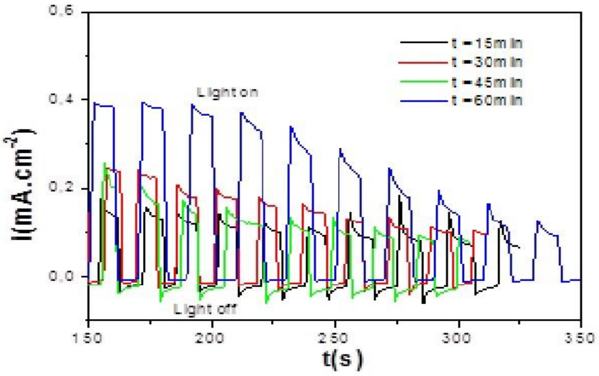

Fig.4: Photo-current measurement of Cu_2O films deposited at pH = 6.5, E = -150mV vs. SCE at a different deposition time.

The deposition duration has a direct impact on the photocurrent response of deposited Cu_2O films. It also promotes an ordered crystalline structure and a balanced surface morphology, which in turn enhance charge carrier mobility and collection. Thus, an optimal duration of 60 minutes maximizes light absorption and reduces charge carrier recombination. An organized structure and a well-balanced surface further improve charge extraction and collection. Therefore, precise control of the deposition time is crucial for maximizing the photoelectrochemical performance of copper oxide films.

D. Effect of the pH of the solution

During the synthesis of metal oxides, the pH of the deposition solution plays a crucial role in determining the type of semiconductor (n-type or p-type) that will form. Controlling the pH enables the regulation of the electrical and optical properties of the films, which is essential for applications such as solar cells. Indeed, the frequent use of p-n heterojunctions is employed to enhance charge separation and improve photovoltaic efficiency. In order to achieve an n-type semiconductor, we will investigate how pH affects the structural, electrical, and optical characteristics of Cu_2O films in order to maximize their performance in photoelectrochemical applications.

The experimental evolution of the Cu_2O deposition current, measured in a bath with a pH of 6.5 is shown in Fig. 5.The copper oxide thin films were droped off for 60 minutes at -150 mV vs. SCE.

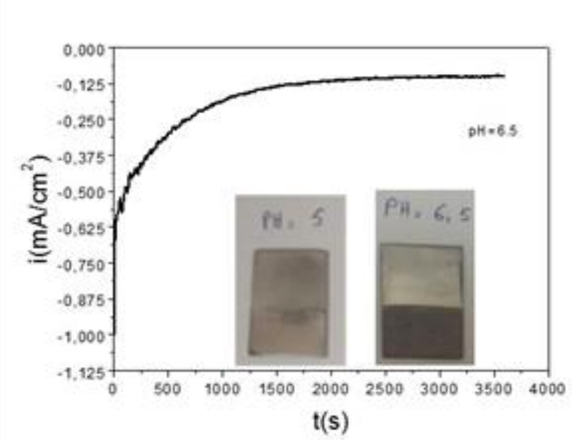

Fig. 5: Evolution of the current of a stainless steel electrode as a function of time in solution, $(CH_3COO)_2Cu$ at 0.01 M and (CH_3COONa) at 0.2 M, T = 60°C, pH = 6.5 and E = -150 mV vs. SCE.

At the beginning of the deposition, the current typically increases rapidly. This initial rise is due to the reduction of Cu^{2+} ions in the electrolyte, leading to the formation of Cu_2O on the electrode surface. The reaction proceeds as Cu^{2+} is reduced to Cu^+, which then forms Cu_2O. After the initial increase, the current might reach as a plate or stabilize. This phase indicates that the deposition process has reached a steady state where the rate of Cu_2O

ISSN: 2961-6603

formation is balanced with the available Cu^{2+} ions in the solution. At this point, the growth of the Cu_2O film continues at a constant rate, and the current stabilizes as the system reaches equilibrium [22]. At the end of the test, the electrode surface is uniformly covered with a brown oxide layer.

The figure above shows the photographic images obtained for thin films deposited at pH = 6.5. We can see that the increase of the pH from 5 to 6.5 leads to the increase of the thickness of the deposit. This increase is probably due to the increase of OH^- ions in the deposition bath which are responsible for the formation of Cu_2O on the substrate surface [23, 24].

The pH can affect the formation and quality of the film. At different pH levels, the equilibrium between Cu^{2+} and Cu^+ changes, which can result in the formation of different types of copper oxides. The pH also affects the distribution of charge carriers (electrons and holes) in the film [25, 26]. For this purpose, we performed a photo-current (PC) technical characterization in order to confirm the type of semi-conductivity of the films formed at different pH values of the solution (5, and 6.5) (fig.6).

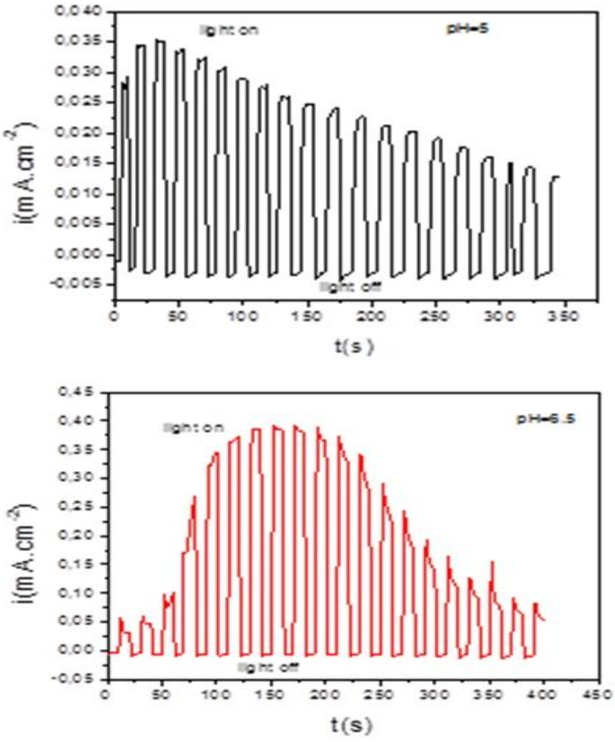

Fig. 6: Photocurrent measurement of copper oxide films deposited at pH = 5 and 6.5.

When light is applied, an increase in photocurrent is observed, as the generation of electron-hole pairs is accelerated. At acidic pH, the electrons generated are more likely to move through the material, and holes can be trapped on the surface or react with H^+ ions present in the solution, thus promoting the generation of anodic photocurrent. At pH 6.5, the copper oxide (Cu_2O) film is of better quality, with improved charge carrier separation, leading to a greater photocurrent response compared to pH 5. For this reason, we have chosen to fix the pH of the deposition bath at 6.5 for the rest of this work.

E. Electrochemical impedance spectroscopy

An electrochemical impedance study (EIS) is of particular interest for analyzing the photoelectrochemical properties of copper oxides, so in order to complete the results found by the photo-current measurement, we made in parallel measurements of electrochemical impedances in linear regime with a sinusoidal signal of amplitude 10 mV. The frequency range explored is from 100 kHz to 10 mHz. According to the results obtained, the impedance diagram of the n-Cu_2O thin film deposited at T = 60°C, pH = 6.5, E = -150 mV vs. SCE and t = 60 min is characterized by the predominance of two processes. At high frequencies, a capacitive semicircle is observed which can be attributed to the charge transfer resistance and the double layer capacitance. This semicircle is followed by an ascending branch characteristic of a diffusional process (fig.7a).

Fig. 7b, shows the spectrum obtained in Bode representation for the thin film of n-type copper oxide. The examination of these results shows the appearance of two time constants the first one is well defined on the recorded diagrams on the other hand, the second constant is not well defined.

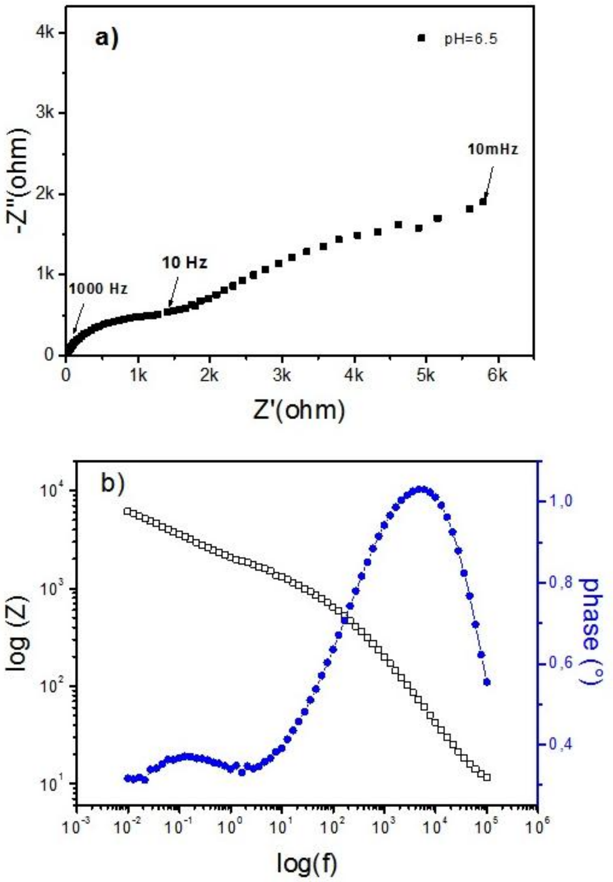

Fig.7: a) Electrochemical impedance diagrams and b) Bode representation plotted in potentiostatic mode at open circuit potential for the n-Cu_2O film.

To ensure optimum performance in applications such as solar cells, an impedance diagram for n-type Cu_2O films shows low charge transfer resistance and good double-layer capacitance, accompanied by rapid electron diffusion [27, 28].

F. XRD characterization

The photoelectric properties of copper oxides are linked to an understanding of their crystalline structure, which affects charge transport, light absorption and carrier generation. In this context, X-ray Diffraction (XRD) is an essential tool for identifying the phases present, assessing crystallite size and material texture, all of which influence photoelectric behavior. XRD analysis therefore provides information to establish a link between crystalline structure and the functional performance of Cu_2O thin films. It is used to define the crystalline composition of deposited oxide films at T = 60°C, pH = 6.5, E = -150 mV vs. SCE and t = 60 min.

According to fig.6 a pure and single polycrystalline cubic phase of Cu_2O has been successfully formed. Indeed, distinct diffraction peaks, corresponding to the (110), (111), (200), (220) and (311) planes are observed at (2θ) values of 29.66, 36.59, 42.52, 61.66 and 73.69° respectively, This result is similar to that obtained by Wijesundera et al [29]. It can also be observed from these spectra that the intensity of the peak along the (111) plane is more important than the other peaks. In addition to the other peaks from ferrite (essential compound of the stainless steel substrate); detected at 2θ positions of 44.69°, 65.33°, 82.71°and 98.99°. No other peak related to copper metal (Cu) or copper (I) oxide (CuO) was observed confirming the purity of our sample, this further supports the deposition mechanism's selectivity.

The DRX diagrams obtained for the Cu_2O films reveal pronounced, narrow and clearly defined peaks located at 2θ angles specific to the crystallographic planes of the Cu_2O phase having a cubic structure. The main peaks are of narrow width at mid-height indicating that the material is of high crystallinity, probably due to good atomic organization in the crystal lattice [30]. Furthermore, the lack of diffuse halos in the baseline of the X-ray diffractograms indicates the absence of amorphous phase, reinforcing the hypothesis of highly crystallized film growth. These structural features favor enhanced optoelectronic properties, crucial for photovoltaic or photoelectrochemical applications.

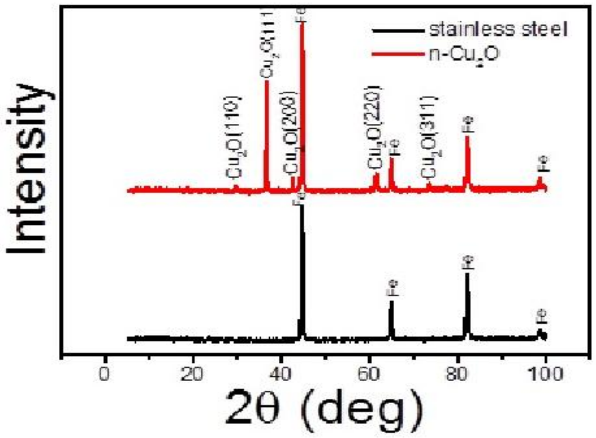

Fig. 6: X-ray diffraction spectra of n-Cu_2O thin films deposited on stainless steel substrate at T= 60°C, pH = 6.5, E =-150 mV vs. SCE and t = 60 min.

G. *Scanning electron microscopy (SEM)*

Scanning electron microscopy (SEM) is an effective analytical method for observing the surface morphology of materials on the nanometric scale. It is particularly suitable for judging the quality, homogeneity and arrangement of thin films employed in photoelectrochemistry.

In this work, SEM analysis of deposited Cu_2O films highlights a uniform surface composed of highly crystallized grains, mainly in the form of cubes, typical of the Cu_2O Figure (7a) crystal structure. The film exhibits a dense, crack-free structure with no excessive porosity, attesting to its mechanical stability and ability to carry loads optimally.

As for EDX analysis, it reveals a notable dominance of copper (Cu) and oxygen (O), presenting a Cu/O atomic ratio of around 2:1, which is in line with values often cited in the literature for Cu_2O [31], moreover no impurities were detected (Figure 7b), attesting to the purity of the deposit. These morphological and elemental observations are in good agreement with the data from X-ray diffraction (XRD), which also corroborate the presence of the Cu_2O phase and underline a satisfactory crystallinity of the material.

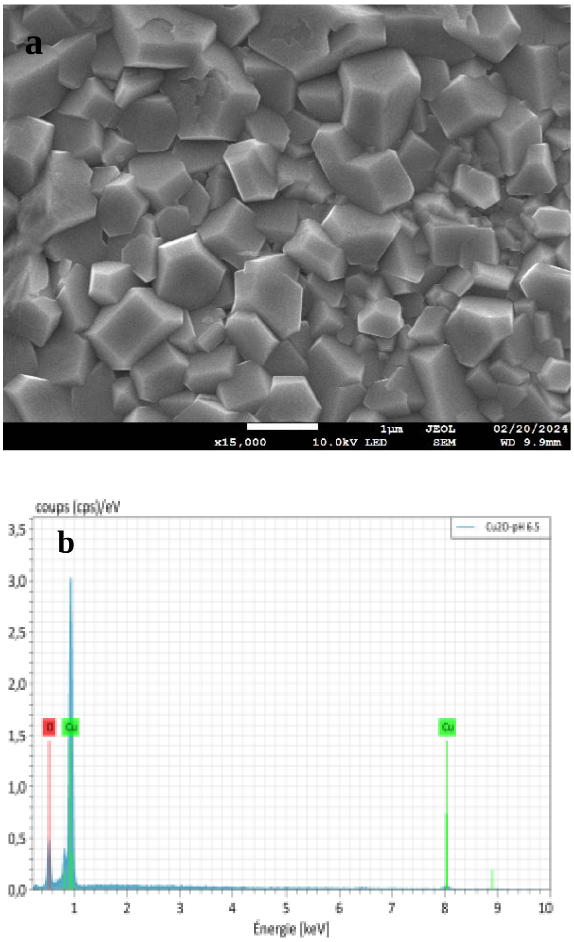

Fig.7: SEM image (a) and EDX spectrum (b) of electrodeposited n-Cu_2O thin films deposited on stainless steel substrate at T = 60°C, pH = 6.5, E = -150 mV vs. SCE and t = 60 min.

III. CONCLUSIONS

Optimizing the properties of n-type Cu_2O thin films is a crucial step in developing efficient photovoltaic devices, particularly for creating effective p-n homojunctions. In this study, we investigated the effects of deposit parameters on the structural and electrochemical properties of Cu_2O films synthesized by chronoampérometry on a stainless steel substrate.

We obtained stable n-type Cu_2O films by setting specific conditions, such as a deposition temperature of 60 °C, a pH of 6.5, a potential applied of -150 mV vs. SCE, and a deposition time of 60 minutes. The X-ray diffraction (XRD) investigations confirmed a cubic crystalline structure with a preferred orientation (111), SEM observations revealed a uniform, nanostructured morphology of the films obtained, characterized by a low defect density and homogeneous substrate coverage, while the electrochemical impedance spectroscopy (EIS) revealed a dominating charge transfer process followed by a diffusional step. These findings suggest that n-type CuO films have promise for use in optoelectronic and photovoltaic systems.

This study highlights how crucial it is to optimize the synthesis parameters in order to enhance the materials photoelectrochimical properties. She also opens up promising prospects for the development of high-performance solar cells based on p-n oxyde of copper, advancing renewable energy technology in the process.

ACKNOWLEDGMENT

The authors would like to thank the Center for Scientific and Technical Research in Physical and Chemical Analysis (CRAPC) of Bejaia, Algeria for samples characterization.

In memory of the late Professor Saïdani Boualem, for his invaluable contributions to this work and to numerous projects in our laboratory.

REFERENCES

[1] K. Rajeshwar, P. Singh, and J. DuBow, "Energy conversion in photoelectrochemical systems - A review," Electrochimica Acta, vol. 23, pp. 1117–1144, 1978.

[2] M. Abdelfatah, J. Ledig, A. El-Shaer, A. Wagner, V. Marin-Borras, A. Sharafeev, P. Lemmens, M. Mohamed Mosaad, A. Waag, and A. Bakin, "Fabrication and characterization of low cost Cu_2O/ZnO:Al solar cells for sustainable photovoltaics with earth abundant materials," Solar Energy Materials and Solar Cells, vol. 145, pp. 454–461, 2016.

[3] A. Aruchamy and A. Fujishima, "Photoanodic behaviour of Cu_2O corrosion layers on copper electrodes," Journal of Electroanalytical Chemistry and Interfacial Electrochemistry, pp. 125–136, 1989.

[4] I. Y. Bouderbala, A. Herbadji, L. Mentar, A. Beniaiche, and A. Azizi, "Optical properties of Cu_2O electrodeposited on FTO substrates: Effects of Cl^- concentration," Journal of Electronic Materials, vol. 47, no. 3, pp. 2000–2008, 2018.

[5] P. Wang, H. Wu, Y. Tang, R. Amal, and Y. H. Ng, "Electrodeposited Cu_2O as photoelectrodes with controllable conductivity type for solar energy conversion," Journal of Physical Chemistry C, vol. 119, pp. 26275–26282, 2015.

[6] A. E. Rakhshani, "Preparation, characteristics and photovoltaic properties of cuprous oxide—A review," Solid-State Electronics, vol. 29, no. 1, pp. 7–17, 1986.

[7] M. M. Elmahdy and A. El Shaer, "Structural, optical and dielectric investigations of electrodeposited p-type Cu_2O," Journal of Materials Science: Materials in Electronics, vol. 30, pp. 19894–19905, 2019.

[8] M. Yurddaskal, T. Dikici, and E. Celik, "Effect of annealing temperature on the surface properties and photocatalytic efficiencies of Cu_2O/CuO structures obtained by thermal oxidation of Cu layer on titanium substrate," Ceramics International, vol. 42, no. 8, pp. 10208–10214, 2016.

[9] D. S. C. Halin, I. A. Talib, A. R. Daud, and M. A. A. Hamid, "Characterizations of cuprous oxide thin films prepared by sol-gel spin coating technique with different additives for the photoelectrochemical solar cell," Applied Mechanics and Materials, vols. 754–755, pp. 1141–1145, 2015.

[10] K. Yamanaka, "Anodically electrodeposited iridium oxide films (AEIROF) from alkaline solutions for electrochromic display devices," Japanese Journal of Applied Physics, vol. 28, no. 4, pp. 632–637, 1989.

[11] T. Yang, Y. Ding, C. Li, N. Yin, X. Liu, and P. Li, "Potentiostatic and galvanostatic two-step electrodeposition of semiconductor Cu_2O films and its photovoltaic application," Journal of Alloys and Compounds, vol. 727, pp. 9–14, 2017.

[12] A. Herbadji, I. Y. Bouderbala, L. Mentar, and A. Azizi, "Effect of copper sulfate concentration on the electrochemical nucleation process, growth and properties of n-type Cu_2O thin films," Russian Journal of Electrochemistry, vol. 55, pp. 1336–1349, 2019.

[13] H. Benathmane, H. Belhadj, M. Guemmez, and A. Azizi, "Effect of bath temperature on the efficiency and properties of Cu_2O/ZnS/ZnO heterojunctions thin film prepared by electrodeposition and chemical bath deposition methods," Optical Materials, vol. 148, p. 114842, 2024.

[14] J. A. Assimos and D. Trivich, "Photovoltaic properties and barrier heights of single crystal and polycrystalline Cu_2O contacts," Journal of Applied Physics, vol. 44, no. 4, p. 1687, 1973.

[15] J.-N. Nian, C.-C. Tsai, P.-C. Lin, and H. Teng, "Elucidating the conductivity-type transition mechanism of p-type Cu_2O films from electrodeposition," Journal of the Electrochemical Society, vol. 156, no. 7, pp. H567–H573, 2009.

[16] F. S. B. Kafi, K. M. D. C. Jayathileka, R. P. Wijesundera, and W. Siripala, "Fermi-level pinning and effect of deposition bath pH on the flat-band potential of electrodeposited n-Cu_2O in an aqueous electrolyte," physica status solidi (b), vol. 253, no. 9, pp. 1965–1969, 2016.

[17] A. Herbadji, I. Y. Bouderbala, L. Mentar, and A. Azizi, "Effect of copper sulfate concentration on the electrochemical nucleation process, growth and properties of n-type Cu_2O thin films," Russian Journal of Electrochemistry, vol. 55, pp. 1336–1349, 2019.

[18] M. Paunovic and M. Schlesinger, Fundamentals of Electrochemical Deposition, 2nd ed. Hoboken, NJ, USA: Wiley, 2006.

[19] P. Qiu, S. Xu, K. Zhang, Z. Jiang, D. Gong, and C. Chen, "Influence of deposition potential on the photoelectrochemical cathodic protection behavior of n-type Cu@Cu_2O films," Journal of Electroanalytical Chemistry, vol. 882, p. 114984, 2021.

[20] Nazakat Ali, S. Hussain, M. Waqas, M. Faheem, N. Ahmad, A. Ali, M. Yasir Ali, K. Mahmood, and Lukas Schmidt-Mende, "Charge transfer in copper oxide thin films deposited at different electrodeposition potential," Physica B: Condensed Matter, vol. 659, p. 414881, 2023.

[21] Asyikin Sasha Mohd Hanif, Siti Aisyah Azmal, Mohd Khairul Ahmad, and Fariza Mohamad, "Effect of deposition time on the electrodeposited n-Cu_2O thin film," Applied Mechanics and Materials, vols. 773–774, pp. 677–681, 2015.

[22] S. Laidoudi, A. Y. Bioud, A. Azizi, G. Schmerber, J. Bartringer, S. Barre, and A. Dinia, "Growth and characterization of electrodeposited Cu_2O thin films," Semiconductor Science and Technology, vol. 28, no. 11, p. 115005, 2013.

[23] C. Wang, J. P. Xu, S. Shi, Y. Zhang, Z. Liu, X. Zhang, S. Yin, and L. Li, "The structural, optical and photoelectrical properties of Cu_2O films electrodeposited in different pH," RSC Advances, vol. 5, pp. 1–10, 2015.

[24] Z. Luo, Y. Su, S. Yue, Q. Yu, H. Zhang, and J. Zhang, "Electrodeposition of copper nanopowder with controllable morphology: Influence of pH on the nucleation/growth mechanism," Journal of Solid State Electrochemistry, vol. 25, no. 5, pp. 1611–1621, 2021.

[25] I. R. Hamdani and A. N. Bhaskarwar, "Tuning of the structural, morphological, optoelectronic and interfacial properties of electrodeposited Cu_2O towards solar water-splitting by varying the deposition pH," Solar Energy Materials and Solar Cells, vol. 240, p. 111719, 2022.

[26] Aitbara Adel, Redouani Locif, Bouderbala Ibrahim Yaacoub, Herbadji Abdelmadjid, Rabhi Selma, and Bouras Imed-Eddine, "pH-dependent deposition of Cu_2O thin films: Tuning defect states and electronic properties for improved energy conversion applications," Applied Physics A, vol. 131, no. 2, p. 105, 2025.

[27] B. Padha, S. Verma, P. Mahajan, V. Gupta, A. Khosla, and S. Arya, "Role of electrochemical techniques for photovoltaic and supercapacitor applications," Critical Reviews in Analytical Chemistry, vol. 54, no. 4, pp. 707–741, 2024.

[28] Mahmoud Abdelfatah, Nourhan Darwesh, Hoda Atta, Amr M. Beltagi, Baoquan Sun, Abdelhamid El-Shaer, and Walid Ismail, "Inverting

electrodeposited nanostructured Cu_2O thin films from n-type to p-type semiconductors and variation of their physical and photoelectrochemical properties for optoelectronic applications," Ceramics International, vol. 49, no. 18, pp. 30732–30743, 2023.

[29] R. P. Wijesundera, M. Hidaka, K. Koga, M. Sakai, and W. Siripala, "Growth and characterisation of potentiostatically electrodeposited Cu_2O and Cu thin films," Thin Solid Films, vol. 500, pp. 241–246, 2005.

[30] H. Solache-Carranco, G. Juárez-Díaz, A. Esparza-García, M. Briseño-García, M. Galván-Arellano, J. Martínez-Juárez, G. Romero-Paredes, and R. Peña-Sierra, "Photoluminescence and X-ray diffraction studies on Cu_2O," Journal of Luminescence, vol. 129, no. 12, pp. 1483–1487, 2009.

[31] E. Kutlu-Narin, P. Narin, B. Emre, and S. B. Lisesivdin, "Influence of pH value of precursor on growth, structural, and optical properties of Cu_2O thin films grown in Mist-CVD," Physica B: Condensed Matter, vol. 681, p. 415860, 2024.

ISSN: 2961-6603