

Morphological and structural properties of CuO thin films prepared by the sol-gel method

Zerina SAKIĆ ^{1,2}, Almedina MODRIĆ-ŠAHBAZOVIĆ ^{1,*}, Sanjin GUTIĆ ², Maja ĐEKIĆ ²

¹ Faculty of Natural Sciences and Mathematics, University of Tuzla, Tuzla, Bosnia and Herzegovina

² Faculty of Science, University of Sarajevo, Sarajevo, Bosnia and Herzegovina

*Corresponding author: almedina.modricsahbazovic@untz.ba

Keywords

CuO thin films
spin coating
dip coating
surface morphology
X-ray diffraction

Abstract

In order to investigate the influence of substrate selection, deposition method and drying temperature on the surface properties of the multilayered CuO thin films, a copper precursor solution was deposited onto indium tin oxide (ITO)-coated glass and p-type silicon (Si) substrates using spin coating and dip coating. Surface morphology of the CuO thin films was characterised using scanning electron microscopy (SEM) and atomic force microscopy (AFM). The results showed that spin coating yields uniform and homogeneous thin films on both types of substrates, whereas films obtained via dip coating showed significantly higher homogeneity on ITO glass than on the p-type Si substrate. The crystal structure of the CuO thin films was examined using X-ray diffraction (XRD), revealing a monoclinic crystal structure with a preferred growth orientation along the (110) plane. XRD analysis further indicated that larger nanoparticles were formed on the ITO glass substrate and at higher drying temperatures. The XRD-derived crystallite size was approximately 5 nm on the ITO glass substrate and 2 nm on the p-type Si substrate.

History

Received: 05-06-2026

Revised: 26-08-2026

Accepted: 03-09-2026

1. Introduction

Nanocrystalline thin films with thicknesses of several micrometres or less have a wide range of applications. They are commonly used in optical devices, magnetic systems, electrochemical cells and more [1-3]. The surface morphology and structural characteristics of thin films and coatings play an important role in determining their functional properties and performance [4]. These diverse applications have motivated extensive research into suitable semiconductor materials, among which copper oxide (CuO) stands out due to its cost-effectiveness, low toxicity and excellent optoelectronic properties [5,6]. It is frequently utilised in the fabrication of solar cells because of its high solar radiation absorption and low thermal emissivity [7]. Copper oxide exists in two semiconducting phases: copper(II) oxide (CuO), also known as tenorite and copper(I) oxide (Cu₂O),

known as cuprite [8]. In some cases, a compound of these two oxides, a metastable oxide (Cu₄O₃), can also be formed [9]. CuO is considered an ideal candidate for use as a sensing material in environmental protection applications due to its favourable properties, such as a high absorption coefficient, good thermal conductivity and strong adaptability to environmental conditions [10]. This material is a p-type transition-metal oxide semiconductor with a band gap of 1.2 – 2.1 eV. It crystallises in a monoclinic crystal structure with lattice parameters $a = 4.685 \text{ \AA}$, $b = 3.423 \text{ \AA}$, $c = 5.132 \text{ \AA}$ and $\beta = 99, 52^\circ$ [11].

The application of CuO is highly dependent on its morphology, which is influenced by numerous parameters such as copper salt concentration, solvent type, drying and annealing temperatures, number of deposited layers, withdrawal speed, substrate nature, fabrication technique and others [12]. Various techniques have been employed for the fabrication of CuO thin films, including RF magnetron sputtering [13], physical vapour deposition [14], chemical vapour deposition [15] and



This work is licensed under a Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) license

the sol-gel method [16]. Among these, the sol-gel method has attracted considerable attention due to its simple deposition procedure, ease of chemical composition control and cost-effective preparation for obtaining high-quality thin films [17].

In this study, the sol-gel deposition methods employed were dip coating (immersion method) and spin coating (rotation method). These techniques do not require complex equipment or stringent production conditions, making them cost-effective and easily scalable for large-scale manufacturing. Both methods are suitable for depositing a wide range of materials, including various oxides, polymers and composites. This level of flexibility is often limited in thermal or electrochemical methods, which may require specific conditions for each material. Moreover, spin coating and dip coating typically operate at lower temperatures than thermal methods and do not require high-vacuum environments. The aim of this study is to compare the structural properties, chemical composition, crystallinity and surface topography of CuO thin films prepared using two sol-gel methods: spin coating and dip coating. In addition, this work seeks to determine whether the drying temperature of individual layers affects these properties of thin CuO films. The novelty of the present study lies in the systematic investigation of the combined effects of the deposition method, substrate type and drying temperature of individual layers on the properties of multilayered CuO thin films.

2. Experimental

2.1 Thin film fabrication

To prepare the CuO precursor solution, the solvent $C_3H_8O_2$ (2-methoxyethanol), $\geq 99\%$ purity, purchased from Carl ROTH (Germany), was mixed with C_2H_7NO (monoethanolamine), $\geq 98\%$ purity, purchased from Sigma-Aldrich (USA), which served as a stabilising agent, using a magnetic stirrer. After thorough mixing of the solvent and stabiliser, $Cu(CH_3COO)_2 \cdot H_2O$ (copper(II) acetate monohydrate), $\geq 98\%$ purity, purchased from Carl ROTH (Germany), supplied as a powder (500 g package), was added at a molar concentration of 0.3 M. The solution was stirred for 10 minutes until the powder was completely dissolved. The amount of monoethanolamine used was in a 3:1 mole ratio relative to the copper acetate. The resulting precursor solution was left to rest for 24 hours before being used for substrate deposition (Fig. 1).

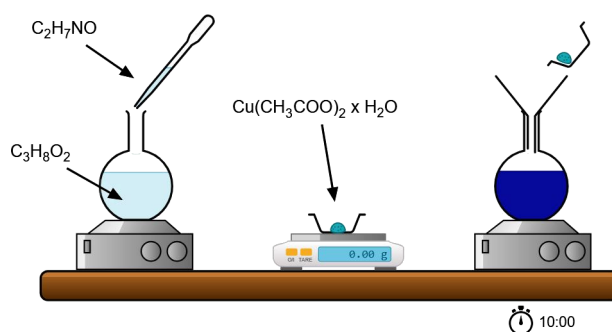


Figure 1. Solution preparation

The copper precursor solution was applied to substrates with dimensions 1.5×2 cm, made of ITO glass (glass coated with indium tin oxide) and p-type Si. The substrates were first thoroughly cleaned in an ultrasonic bath for 10 minutes each, using acetone ($(CH_3)_2CO$), ethanol (C_2H_5OH) and distilled water, in sequence. The dried substrates were then cleaned for 15 minutes in the Ossila L2002A3 UV ozone cleaner to further remove organic contaminants, resulting in ultra-clean substrates and ensuring better adhesion of the film to the substrate.

Four-layered CuO thin films were produced by depositing the solution onto pre-cleaned substrates using two methods: spin coating and dip coating. Following the parameter optimisation, a single layer was fabricated through spin coating by dispensing $50\ \mu l$ of the solution onto the centre of a substrate, which was mounted in a substrate holder of the Ossila L2001A3-U1 spin coater. The solution was spread over the substrate by rotating it at a speed of 2000 rpm for 30 seconds. Following each cycle, the deposited layer was dried in an oven at $150\ ^\circ C$ for 10 minutes.

For the production of a single layer by dip coating, the Ossila L2006A1 dip coater was set to a substrate immersion speed of 5 mm/s and an extraction speed of 0.1 mm/s. In this process, 1 cm of the substrate was immersed in the solution for 10 seconds before extraction. In order to investigate the influence of drying temperature on the structural and surface properties of thin films, a single layer was dried for 10 minutes in two ways: at room temperature in ambient air and in a preheated oven at $150\ ^\circ C$. Multilayered CuO thin films were obtained by repeating the deposition and drying process four consecutive times.

Finally, the fabricated CuO thin films were annealed for 1 hour at $600\ ^\circ C$ in ambient air using a MicroAnalytix muffle furnace MF 207. For each experimental condition, one specimen was

independently prepared and characterised. Six thin-film samples were selected for further analysis, and their deposition parameters are presented in Table 1.

Table 1. Deposition parameters of six selected CuO films

Sample	Method of fabrication	Layer drying temperature, °	Substrate
S1	spin coating	150	ITO glass
S2			p-type Si
D1	dip coating	150	ITO glass
D2			p-type Si
D3		22	ITO glass
D4			p-type Si

2.2 Characterisation techniques

Topography and chemical composition of the samples were examined on the JEOL JSM IT 200LA scanning electron microscope (SEM) equipped with an energy-dispersive X-ray spectroscopy (EDS) detector. The images were recorded in high-vacuum mode at accelerating voltages of 5 and 10 kV.

Atomic force microscopy (AFM) was carried out using Nanosurf CoreAFM. Images were acquired with a scan resolution of 256 points/line in dynamic mode using aluminium tips (Nanosurf DynAI), with a nominal frequency of 190 kHz and a constant nominal force of 48 N/m. Processing and analysis of AFM images were performed with Nanosurf software.

The crystal structure of the samples was analysed using a Bruker D8 ADVANCE X-ray diffractometer (XRD) equipped with a Cu anode ($\lambda = 0.154$ nm) and a LYNXEYE XE-T detector. The XRD patterns were taken in the range $2\theta = 20 - 80^\circ$, with a step size of 0.02° , a counting time of 1 s per step, tube voltage of 40 kV and tube current of 40 mA. Phase identification and quantification were performed using DIFFRAC.EVA software.

3. Results and discussion

SEM micrographs of the analysed CuO thin films are shown in Figure 2. The CuO thin films deposited on ITO glass substrate (Figs. 2a, 2c and 2e) exhibit randomly distributed, approximately spherical surface features with relatively well-defined particle boundaries. A comparison of these samples indicates differences in the apparent surface feature size and morphology, which were quantitatively evaluated using ImageJ software

based on the Feret diameter. The obtained apparent Feret diameters were 0.245, 0.228 and $0.186 \mu\text{m}$ for S1, D1 and D3, respectively, with S1 exhibiting the largest apparent surface features. The apparent surface feature sizes obtained for the present CuO films are also comparable with previously reported CuO films prepared by spray pyrolysis, for which an average granule size of approximately 200 nm was reported [18]. These values represent the apparent lateral dimensions of the surface features noticed in the SEM micrographs.

EDS results (Table 2) confirmed Cu and O in all films, with additional signals from the substrates. D1 showed the highest Cu contribution, while S1 and D3 had comparable lower Cu contents. The In signal originated from the ITO layer, whereas Si and Ca originated from the glass substrate. Although D3 had the smallest Feret diameter, its Cu content was comparable to S1, indicating that surface feature size was not directly related to Cu concentration.

Table 2. EDS elemental composition of the CuO thin films

Sample	Element	Mass %	Atom %
S1	O	28.12	62.29
	Si	12.45	15.71
	Ca	2.32	2.05
	Cu	9.33	5.21
	In	47.77	14.74
S2	O	3.92	9.13
	Si	46.59	61.83
	Cu	49.49	29.04
D1	O	26.03	60.34
	Si	10.95	14.45
	Cu	18.60	10.86
	In	44.43	14.35
D2	O	2.99	5.57
	Si	82.42	87.58
	Cu	14.59	6.85
D3	O	25.61	59.70
	Si	11.78	15.64
	Ca	3.19	2.97
	Cu	9.14	5.36
	In	50.28	16.33
D4	Si	82.96	91.68
	Cu	17.04	8.32

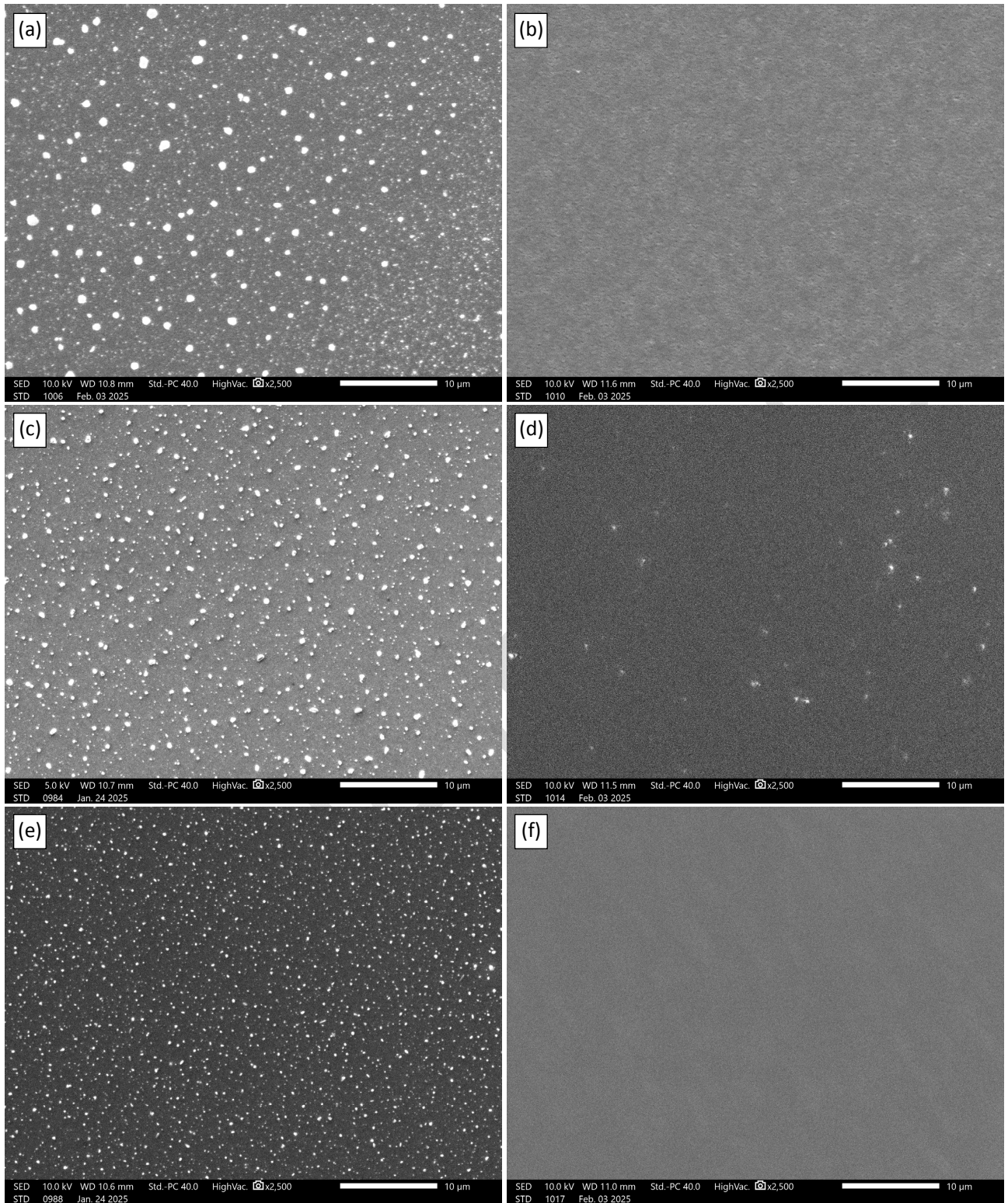


Figure 2. SEM micrographs of CuO thin film samples obtained by spin coating and dip coating on ITO glass and p-type Si substrates: (a) S1, (b) S2, (c) D1, (d) D2, (e) D3 and (f) D4

The films deposited on the Si substrate (Figs. 2b, 2d and 2f) exhibited less clearly distinguishable individual particles and comparatively homogeneous or porous surface morphologies. Such substrate-dependent differences in the morphology of CuO thin films have also been reported in previous studies [19]. In sample S2 (Fig. 2b), particle-like features forming

a disordered porous structure can be noticed. This morphology may be associated with the Si substrate and the applied thermal treatment under the specific experimental conditions used in this study. The EDS analysis of sample S2 showed the highest Cu contribution among the Si-substrate films, whereas samples D2 and D4 exhibited substantially stronger Si

signals and lower Cu contributions. The pronounced Si contribution indicates that the EDS measurements are strongly influenced by the underlying substrate, particularly in regions where the CuO layer is relatively thin or porous. The porous morphology may allow deeper penetration of the electron beam and consequently increase the contribution of the substrate to the measured spectrum.

A comparison of the dip-coated Si-substrate samples D2 and D4 also shows a difference in the detected Cu contribution under the applied drying conditions. Sample D2, dried at 150 °C, showed a higher Cu contribution than sample D4, which was dried at room temperature. However, these differences should be interpreted together with the noticed SEM morphology and the strong Si contribution rather than as a direct measure of film thickness or deposition efficiency. The low oxygen contribution noticed for some samples should likewise not be interpreted as evidence for the

absence of CuO, since the EDS signal is affected by the electron-beam interaction volume and the underlying substrate. Overall, under the specific deposition, drying and annealing conditions employed in this study, the Si-substrate CuO films exhibited less clearly distinguishable surface features and a stronger contribution from the underlying substrate in the EDS spectra. These notations indicate that the substrate influenced the morphology and EDS response of the CuO films under the specific experimental conditions investigated.

Based on the analysis of the SEM micrographs, which confirmed that spin coating provides more homogeneous thin films, samples S1 and S2 were selected for further AFM analysis. Additionally, samples D1 and D3 were also analysed by AFM to demonstrate that films obtained by dip coating are significantly rougher. AFM images, presented in Figure 3, show both 2D and 3D topographies of the selected CuO thin film samples.

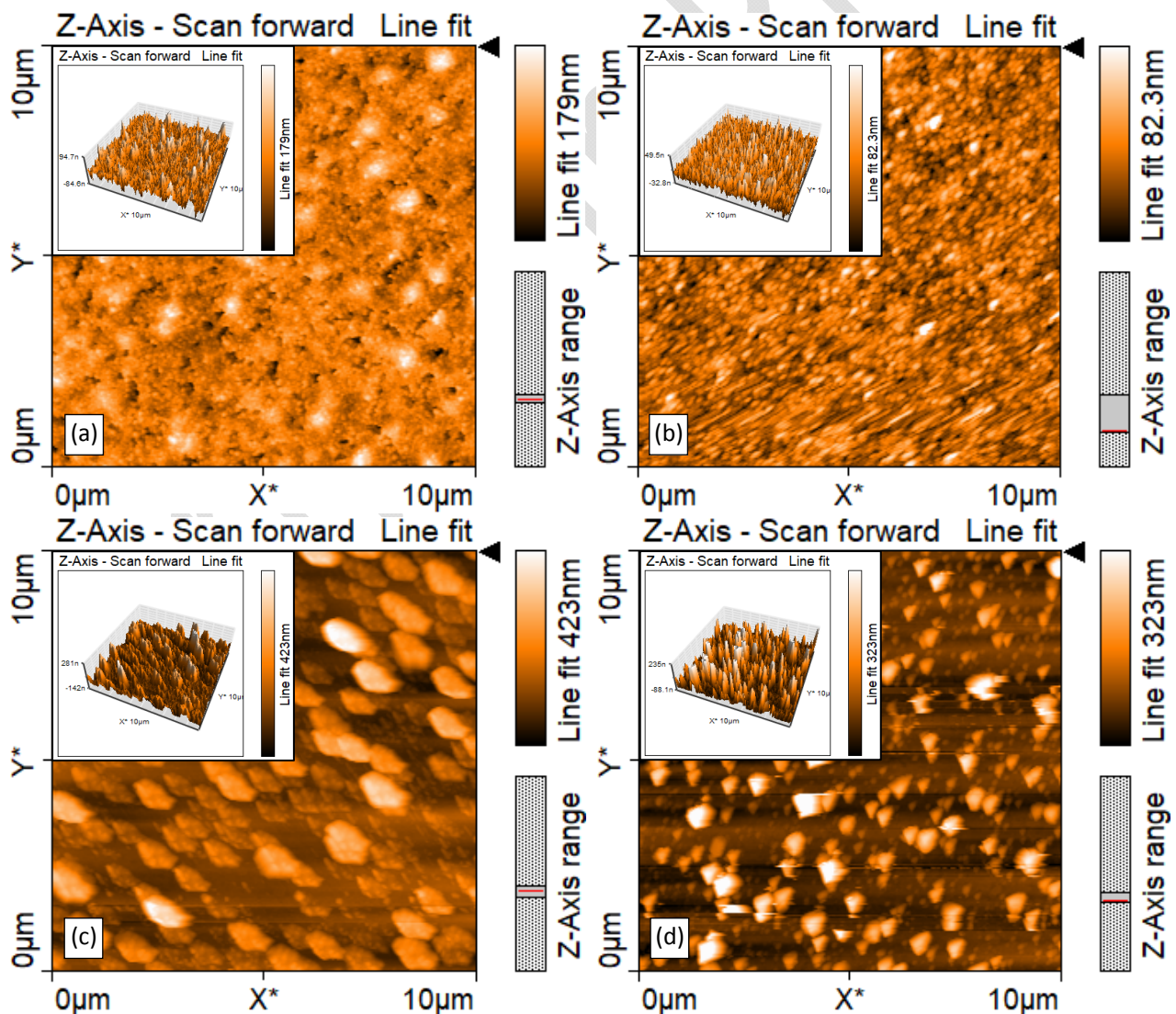


Figure 3. AFM 2D and 3D topography of CuO thin film samples obtained by spin coating and dip coating on ITO glass and p-type Si substrates: (a) S1, (b) S2, (c) D1 and (d) D3

Table 3. AFM parameters of CuO thin film samples obtained by spin coating and dip coating on ITO glass and p-type Si substrates

Sample	Ra , nm	Rz , nm	Sq , nm	L , nm
S1	15.7 ± 1.7	127.8 ± 19.9	21.9	347.5 ± 41.7
S2	8.5 ± 0.6	60.4 ± 9.1	11.4	215.4 ± 22.4
D1	46.8 ± 11.4	249.8 ± 28.0	65.9	1184.1 ± 162.3
D3	35.6 ± 4.4	225.2 ± 36.0	61.2	640.5 ± 70.8

The grains on the silicon substrate (Fig. 3b) are considerably finer than those deposited on the ITO glass substrate (Figs. 3a, 3c and 3d). In order to further elucidate these morphological differences, the AFM images were analysed to determine the surface roughness and morphological characteristics of the CuO thin films. The arithmetical mean height (Ra) and maximum height (Rz) were determined from 10 line profiles distributed approximately evenly across the surface and extracted from each AFM image, while the root mean square height (Sq), as an area roughness parameter, was calculated over the entire scanned area presented in Figure 3. The characteristic grain length (L) was determined from the AFM topographic images by identifying 10 randomly selected individual grains. The results are presented in Table 3.

The measured Sq value for the sample S1 is consistent with those previously reported for spin-coated CuO thin films deposited on ITO glass substrate, for which root mean square height values in the range of approximately 12 – 36 nm were reported, depending on the sol ageing time [20]. The surface roughness of CuO thin films is influenced by both the underlying substrate and the deposition method. Films deposited on ITO glass substrate may exhibit higher Sq values than those deposited on Si, likely due to differences in substrate topography and film-substrate interfacial interactions, as previously reported for Nb(Zn)-doped dip-coated ITO films deposited on microscopic glass, SiO₂/glass and Si substrates [21].

Figure 4 shows the XRD patterns obtained for CuO thin film samples, along with the standard CuO reference pattern from the International Centre for Diffraction Data (ICDD), card no. 00-041-0254, represented by vertical reference lines at the top of the figure. The diffraction peaks corresponding to the CuO phase were assigned to the (110), (002), ($\bar{1}11$), (111), (200), ($\bar{1}12$) ($\bar{2}02$), (020), (202) and ($\bar{1}13$) crystallographic planes of monoclinic CuO. The corresponding crystallographic

plane assignments are indicated in Figure 4b, which represents the XRD pattern of the CuO thin film deposited on the p-type Si substrate, where the characteristic diffraction peaks of the CuO phase can be clearly resolved. For the samples deposited on ITO glass, shown in Figures 4a, 4c and 4d, the presence of diffraction signals originating from the ITO glass makes it difficult to clearly resolve some of the characteristic CuO peaks. Therefore, these peaks are not individually indexed in these diffraction patterns. Based on the obtained XRD spectra, various microstructural parameters can be calculated, such as crystallite size, texture coefficient, lattice spacing, lattice parameters, microstrain and dislocation density.

The crystallite size of the deposited CuO thin films was estimated using the Scherrer equation [22]:

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

where D is the crystallite size, K is the Scherrer constant (typically taken as 0.94, but it can vary depending on the actual shape of nanocrystallites), λ is the wavelength of the X-ray radiation, θ is the Bragg angle and β is the full width at half maximum (FWHM) of the XRD peak, expressed in radians.

Based on the obtained crystallite size, the dislocation density (δ) was calculated using the following equation [22]:

$$\delta = \frac{1}{D^2}. \quad (2)$$

The microstrain (ϵ) induced in the analysed thin films can be determined using the following equation [23]:

$$\epsilon = \frac{\beta}{4 \tan \theta}. \quad (3)$$

The lattice spacing between two successive planes (d) was calculated using XRD data and Bragg's law [24]:

$$n\lambda = 2d \sin \theta. \quad (4)$$

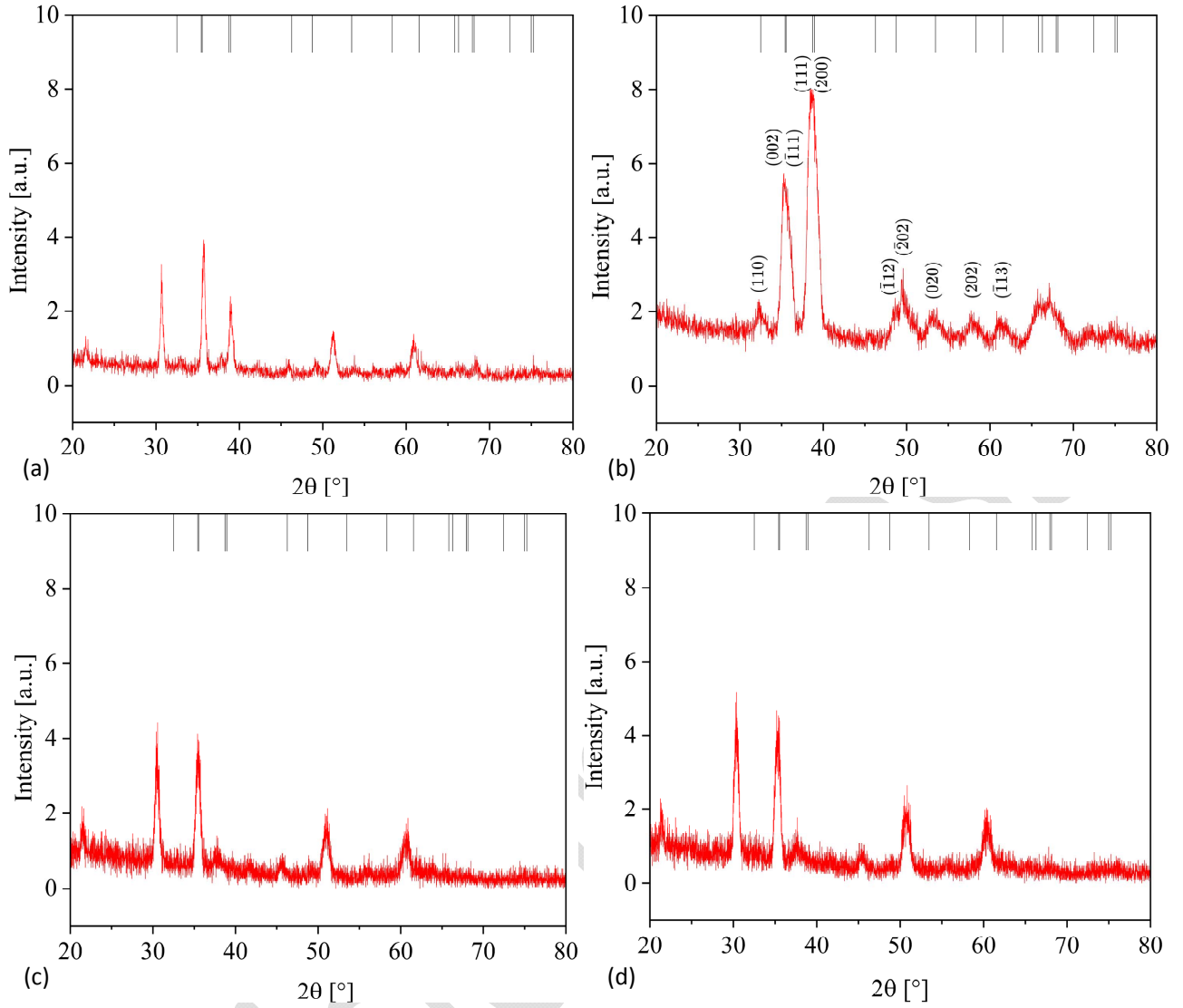


Figure 4. XRD spectra of CuO thin film samples obtained by spin coating and dip coating on ITO glass and p-type Si substrates: (a) S1, (b) S2, (c) D1 and (d) D3

Table 4 presents the values of the Bragg angles θ and FWHM corresponding to the specified planes, along with the calculated values of crystallite size D , dislocation density δ , microstrain ε and the lattice spacing d of the CuO thin films. According to the obtained results, the crystallite sizes are significantly larger on the ITO glass substrate, with approximate values around 5 nm, while on the p-type Si substrate, the crystallites are around 2 nm in size. Slightly larger crystallites were

obtained using dip coating compared to spin coating. The crystallite sizes obtained in the present study (2 – 5 nm) are comparable to values reported in previous studies, with CuO crystallite sizes of approximately 4 – 5 nm [24]. As expected, within the dip coating, layers dried at 150 °C resulted in larger crystallites than those dried at room temperature, which is consistent with the SEM analysis showing larger apparent surface features in the films dried at higher temperatures.

Table 4. Calculated values of the examined CuO thin film samples corresponding to the selected diffraction peaks

Sample	Plane (hkl)	2θ , °	FWHM, °	θ , rad	D , nm	d , Å	$\delta \times 10^{16}$, lines/m ²	$\varepsilon \times 10^{-3}$
S1	($\bar{2}02$)	49.22	1.79	0.03	5.09	1.85	3.87	17.1
S2	($\bar{2}02$)	49.54	4.57	0.08	2.00	1.84	24.96	43.2
D1	($\bar{1}13$)	60.67	1.84	0.03	5.23	1.53	3.66	13.7
D3	($\bar{1}13$)	60.96	1.86	0.03	5.17	1.52	3.74	13.8

The density of dislocations is influenced by the type of substrate used, and it is significantly lower for the ITO glass substrate compared to the p-type Si substrate. In addition, it is obvious that the drying temperature of the layers affects the dislocation density, with higher drying temperatures of the layers leading to a lower dislocation density, which corresponds to a more ordered crystal structure [25]. The microstrain is significantly higher when p-type Si is used as the substrate compared to ITO glass. Variations in peak intensity may be associated with differences in crystallinity, preferred orientation and crystallite development, as well as with the contribution of the substrate used, particularly the ITO glass for samples S1, D1 and D3, whereas shifts in peak position may arise from changes in lattice parameters, residual stress and microstrain, defects, composition or other structural modifications. The obtained values for the lattice spacing between two successive planes, presented in Table 4, are in agreement with the data given in the ICDD card no. 00-041-0254. Moreover, the values of the lattice parameters from the ICDD card for CuO also match the values presented in Table 5 for each of the analysed samples, which were calculated using the equation for the monoclinic structure [26]:

$$\frac{1}{d^2} = \frac{1}{\sin^2 \theta} \left(\frac{h^2}{a^2} + \frac{k^2 \sin^2 \theta}{b^2} + \frac{l^2}{c^2} - \frac{2h \cos \theta}{ac} \right), \quad (5)$$

where d is the lattice spacing between two successive planes, a , b , c and θ are the lattice parameters and h , k and l are the Miller indices for the planes.

To determine the crystal growth orientation, the texture coefficient (TC) was calculated using the following equation [27]:

$$TC(hkl) = \frac{\frac{I_{hkl}}{I_{0;hkl}}}{\frac{1}{N} \sum \frac{I_{hkl}}{I_{0;hkl}}}, \quad (6)$$

where I_{hkl} is the measured intensity of the (hkl) plane, $I_{0;hkl}$ is the reference intensity of the (hkl) plane and N is the number of considered peaks.

For values of $0 < TC < 1$, there are not enough nanoparticles moving in the considered direction, and in this case there is no preferential growth orientation. If $TC > 1$, there are more nanoparticles oriented in the specific direction (hkl), making this direction the preferential growth orientation of the

crystal [4]. The calculated values for the texture coefficient are presented in Table 6. A preferential (110) orientation is analysed only for samples S2 and D1, with TC values of 1.743 and 3.180, respectively, while S1 and D3 show TC(110) values below unity (0.526 and 0.796, respectively). The higher TC(110) value for D1 indicates a stronger preferential orientation along this plane compared with S2, suggesting that the crystallographic texture is dependent on the deposition conditions.

Table 5. Lattice parameters of the examined CuO thin film samples obtained by spin coating and dip coating on ITO glass and p-type Si substrates

Sample	a , Å	b , Å	c , Å	θ , °
S1	5.067	3.399	5.382	88.98
S2	4.647	3.430	4.984	81.40
D1	5.085	3.581	5.282	88.26
D3	4.604	3.115	4.900	75.53

Table 6. Texture coefficient for some of the analysed planes of CuO thin film samples obtained by spin coating and dip coating on ITO glass and p-type Si substrates

Sample	TC				
	(110)	($\bar{1}11$)	(200)	($\bar{2}02$)	($\bar{1}13$)
S1	0.526	0.256	0.142	0.149	0.488
S2	1.743	0.396	0.584	0.657	0.735
D1	3.180	0.248	0.059	–	0.516
D3	0.796	0.287	0.066	–	0.640

4. Conclusion

Multilayer CuO thin films were successfully fabricated using spin coating and dip coating, and the influence of substrate type (ITO glass and p-type Si), deposition technique and drying temperature on their properties was investigated.

SEM analysis shows that the surface morphology and apparent surface feature distribution of CuO thin films depend strongly on the deposition method and substrate type. Spin-coated films exhibit a more uniform distribution of surface features compared to dip-coated films. Noticeable differences are also noticed between substrates, particularly ITO glass and p-type Si. In dip-coated films, higher drying temperatures lead to larger particle formation. EDS results additionally indicate variations in Cu content, with the highest mass fraction noticed in spin-coated films on the p-type Si substrate.

AFM analysis confirms that spin coating produces smoother surfaces, with root mean square height values of 21.9 nm and 11.4 nm for S1 and S2, compared to 65.9 nm and 61.2 nm for D1 and D3. The additional AFM parameters, including arithmetical mean height, maximum height and characteristic grain length, further support the noticed differences in surface morphology, with higher roughness and larger characteristic surface features obtained for the dip-coated films.

XRD analysis confirms CuO formation, with crystallite size ranging from 2.00 nm to 5.23 nm and improved structural ordering for ITO-based films and higher drying temperatures. It is evident that deposition conditions and substrate type play a key role in governing the structural and surface properties of CuO thin films.

Acknowledgement

This work was supported by the Federal Ministry of Science and Education of Bosnia and Herzegovina (No. 05-35-3549-1/25). We would like to thank Kerim Hrvat for his assistance with XRD and SEM measurements in Sarajevo.

References

- [1] B. Liang, X. Chen, H. Yuan, X. Wang, G. Hou, Y. Zhao, X. Zhang, Enhancing optical and electrical performances via nanocrystalline Si-based thin films for Si heterojunction solar cells, *ACS Omega*, Vol. 9, No. 50, 2024, pp. 49935-49944, DOI: [10.1021/acsomega.4c09080](https://doi.org/10.1021/acsomega.4c09080)
- [2] A.-M. Florea, S. Caramizoiu, A.-M. Iordache, S.-M. Iordache, B. Bitu, Nanostructured thin films: Properties, fabrication and applications – A short review, *Nanomaterials*, Vol. 15, No. 23, 2025, Paper 1760, DOI: [10.3390/nano15231760](https://doi.org/10.3390/nano15231760)
- [3] J. Cao, Y. Ji, Z. Shao, Nanotechnologies in ceramic electrochemical cells, *Chemical Society Reviews*, Vol. 53, No. 1, 2024, pp. 450-501, DOI: [10.1039/d3cs00303e](https://doi.org/10.1039/d3cs00303e)
- [4] M. Barman, T.K. Barman, P. Sahoo, Trends in corrosion resistance of electroless Ni-B-Mo coatings, *Tribology and Materials*, Vol. 4, No. 1, 2025, pp. 38-55, DOI: [10.46793/tribomat.2025.005](https://doi.org/10.46793/tribomat.2025.005)
- [5] J. Sultana, S. Paul, R. Saha, S. Sikdar, A. Karmakar, S. Chattopadhyay, Optical and electronic properties of chemical bath deposited p-CuO and n-ZnO nanowires on silicon substrates: p-CuO/n-ZnO nanowires solar cells with high open-circuit voltage and short-circuit current, *Thin Solid Films*, Vol. 699, 2020, Paper 137861, DOI: [10.1016/j.tsf.2020.137861](https://doi.org/10.1016/j.tsf.2020.137861)
- [6] S.S. Shariffudin, S.S. Khalid, N.M. Sahat, M.S.P. Sarah, H. Hashim, Preparation and characterization of nanostructured CuO thin films using sol-gel dip coating, *IOP Conference Series: Materials Science and Engineering*, Vol. 99, 2015, Paper 012007, DOI: [10.1088/1757-899X/99/1/012007](https://doi.org/10.1088/1757-899X/99/1/012007)
- [7] G.G. Welegergs, R. Akoba, J. Sacky, Z.Y. Nuru, Structural and optical properties of copper oxide (CuO) nanocoatings as selective solar absorber, *Materials Today: Proceedings*, Vol. 36, No. 2, 2021, pp. 509-513, DOI: [10.1016/j.matpr.2020.05.298](https://doi.org/10.1016/j.matpr.2020.05.298)
- [8] W. El Berjali, V. Colas, S. Ould Saad Hamady, S.S. Ng, N.A. Hamzah, P. Boulet, D. Horwat, J.-F. Pierson, Copper oxide by spin-coating: Cost-effective deposition and post-annealing process for thin films with modulated Cu₂O/CuO phase ratio, *Thin Solid Films*, Vol. 826, 2025, Paper 140762, DOI: [10.1016/j.tsf.2025.140762](https://doi.org/10.1016/j.tsf.2025.140762)
- [9] Z. Jiang, S. Tian, S. Lai, R.D. McAuliffe, S.P. Rogers, M. Shim, D.P. Shoemaker, Capturing phase evolution during solvothermal synthesis of metastable Cu₄O₃, *Chemistry of Materials*, Vol. 28, No. 9, 2016, pp. 3080-3089, DOI: [10.1021/acs.chemmater.6b00421](https://doi.org/10.1021/acs.chemmater.6b00421)
- [10] A. Rydosz, The use of copper oxide thin films in gas-sensing applications, *Coatings*, Vol. 8, No. 12, 2018, Paper 425, DOI: [10.3390/coatings8120425](https://doi.org/10.3390/coatings8120425)
- [11] M. Asadi, S.M. Rozati, Optical and structural properties of nanostructured copper oxide thin films as solar selective coating prepared by spray pyrolysis method, *Materials Science-Poland*, Vol. 35, No. 2, 2017, pp. 355-361, DOI: [10.1515/msp-2017-0054](https://doi.org/10.1515/msp-2017-0054)
- [12] M.S. Jawad, F. Tanveer, R.R. Ahsan, M.A. Rahman, M.M. Billah, Hydrothermal synthesis of CuO nanostructures: Morphology controlled approaches for multifunctional performance – A review, *Journal of Physics and Chemistry of Solids*, Vol. 208, No. 1, 2026, Paper 113018, DOI: [10.1016/j.jpcs.2025.113018](https://doi.org/10.1016/j.jpcs.2025.113018)
- [13] J.F. Pierson, A. Thobor-Keck, A. Billard, Cuprite, paramelaconite and tenorite films deposited by reactive magnetron sputtering, *Applied Surface Science*, Vol. 210, No. 3-4, 2003, pp. 359-367, DOI: [10.1016/S0169-4332\(03\)00108-9](https://doi.org/10.1016/S0169-4332(03)00108-9)
- [14] D. Santos-Cruz, S.A. Mayén-Hernández, F. de Moure-Flores, J. Campos-Álvarez, M. Pal, J. Santos-Cruz, CuO_x thin films by direct oxidation of Cu films deposited by physical vapor deposition, *Results in Physics*, Vol. 7, 2017, pp. 4140-4144, DOI: [10.1016/j.rinp.2017.10.022](https://doi.org/10.1016/j.rinp.2017.10.022)
- [15] K.H. Yoon, W.J. Choi, D.H. Kang, Photoelectrochemical properties of copper oxide thin films coated on an *n*-Si substrate, *Thin*

- Solid Films, Vol. 372, 2000, pp. 250-256, DOI: [10.1016/S0040-6090\(00\)01058-0](https://doi.org/10.1016/S0040-6090(00)01058-0)
- [16] A. Modrić-Šahbazović, A. Smajlagić, Z. Sakić, M. Novaković, N. Latas, M. Popović, M. Đekić, S. Isaković, A. Salčinović Fetić, Role of synthesis temperature in the formation of ZnO nanoparticles via the sol-gel process, *Journal of Crystal Growth*, Vol. 650, 2025, Paper 128003, DOI: [10.1016/j.jcrysgro.2024.128003](https://doi.org/10.1016/j.jcrysgro.2024.128003)
- [17] N. Mustapha, M. Hjiri, Advances in eco-efficient and accelerated sol-gel routes for hybrid nanostructures, *Journal of Sol-Gel Science and Technology*, Vol. 117, No. 2, 2026, Paper 59, DOI: [10.1007/s10971-025-07088-7](https://doi.org/10.1007/s10971-025-07088-7)
- [18] H.Z. Asl, S.M. Rozati, Spray deposited nanostructured CuO thin films: Influence of substrate temperature and annealing process, *Materials Research*, Vol. 21, No. 2, 2018, Paper e20170754, DOI: [10.1590/1980-5373-MR-2017-0754](https://doi.org/10.1590/1980-5373-MR-2017-0754)
- [19] V. Dhanasekaran, T. Mahalingam, Physical properties evaluation of various substrates coated cupric oxide thin films by dip method, *Journal of Alloys and Compounds*, Vol. 539, 2012, pp. 50-56, DOI: [10.1016/j.jallcom.2012.05.092](https://doi.org/10.1016/j.jallcom.2012.05.092)
- [20] C.-J. Chang, C.-W. Lai, W.-C. Jiang, Y.-S. Li, C. Choi, H.-C. Yu, S.-J. Chen, Y. Choi, Fabrication and characterization of p-type semiconducting copper oxide-based thin-film photoelectrodes for solar water splitting, *Coatings*, Vol. 12, No. 8, 2022, Paper 1206, DOI: [10.3390/coatings12081206](https://doi.org/10.3390/coatings12081206)
- [21] M. Gartner, A. Szekeres, S. Simeonov, M. Covei, M. Anastasescu, S. Preda, J.M. Calderon-Moreno, L. Predoana, H. Stroescu, D. Mitrea, M. Nicolescu, Structure, optical and electrical properties of Nb(Zn) doped sol-gel ITO films: Effect of substrates and dopants, *Molecules*, Vol. 29, No. 22, 2024, Paper 5480, DOI: [10.3390/molecules29225480](https://doi.org/10.3390/molecules29225480)
- [22] S.S. Kumar Jacob, I. Kulandaisamy, I.L. Poul Raj, A.A. Abdeltawab, S.Z. Mohammady, M. Ubaidullah, Improved optoelectronic properties of spray pyrolysis coated Zn doped Cu₂O thin films for photodetector applications, *Optical Materials*, Vol. 116, 2021, Paper 111086, DOI: [10.1016/j.optmat.2021.111086](https://doi.org/10.1016/j.optmat.2021.111086)
- [23] S. Hamza, C.O. Ugwuoke, A. Diallo, B. Nouredine, D. Sawzan, F.I. Ezema, Facile synthesis and optical characterization of CuO/Cu(OH)₂ thin film, *Hybrid Advances*, Vol. 4, 2023, Paper 100093, DOI: [10.1016/j.hybadv.2023.100093](https://doi.org/10.1016/j.hybadv.2023.100093)
- [24] J. Jońca, A. Ryzhikov, S. Palussière, J. Esvan, K. Fajerwerk, P. Menini, M.L. Kahn, P. Fau, Organometallic synthesis of CuO nanoparticles: Application in low-temperature CO detection, *ChemPhysChem*, Vol. 18, No. 19, 2017, pp. 2658-2665, DOI: [10.1002/cphc.201700693](https://doi.org/10.1002/cphc.201700693)
- [25] R. Singh, L. Yadav, Shrey, S. Tripathi, Effect of annealing time on the structural and optical properties of n-CuO thin films deposited by sol-gel spin coating technique and its application in n-CuO/p-Si heterojunction diode, *Thin Solid Films*, Vol. 685, 2019, pp. 195-203, DOI: [10.1016/j.tsf.2019.06.026](https://doi.org/10.1016/j.tsf.2019.06.026)
- [26] A.H.O. Alkhayatt, S.K. Muhammad, A.A. Habieb, A.H. Ali, S.H. Mohsen, R.R. Munem, Low annealing temperature effect on structural, and optical properties of CuO nanostructure thin films, *IOP Conference Series: Materials Science and Engineering*, Vol. 871, 2020, Paper 012094, DOI: [10.1088/1757-899X/871/1/012094](https://doi.org/10.1088/1757-899X/871/1/012094)
- [27] R. Amari, A. Mahroug, A. Boukhari, B. Deghfel, N. Selmi, Structural, optical and luminescence properties of ZnO thin films prepared by sol-gel spin-coating method: Effect of precursor concentration, *Chinese Physics Letters*, Vol. 35, No. 1, 2018, Paper 016801, DOI: [10.1088/0256-307X/35/1/016801](https://doi.org/10.1088/0256-307X/35/1/016801)