

Tailoring the Optical, Electrical, and Photo-sensing Properties of Chemically Deposited CdS Thin Films through Copper Doping

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ABSTRACT

Copper (Cu) doping is an effective approach for tailoring the optoelectronic properties of cadmium sulphide (CdS) thin films for photosensor applications. This study systematically investigates the influence of Cu concentration on the thickness, surface morphology, optical, electrical, and photosensing properties of CdS thin films synthesized by chemical bath deposition. Cu-doped CdS thin films containing 0, 0.5, 1.0, 1.5, and 2.0% (v/v) Cu were deposited under identical conditions to isolate the effect of dopant concentration. Increasing Cu concentration reduced the film thickness from 3.00 to 0.42 μm and the surface roughness from 3029.20 to 67.17 $\text{\AA}$, indicating improved film compactness. Optical characterization showed enhanced absorption, extinction coefficient, dielectric response, and optical conductivity, while the optical bandgap increased from 2.07 eV to 2.31 eV at 1.5% Cu. Hall-effect measurements confirmed n-type conductivity for all films, with the highest Hall mobility ($1.81 \times 10^3 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$) and the lowest resistivity ($1.49 \times 10^4 \Omega \text{ cm}$) obtained at 1.5% Cu. The undoped CdS film exhibited the highest photosensitivity (3110.08%) owing to its low dark current, whereas the 0.5% Cu-doped film achieved the highest responsivity (0.0283 mA W^{-1}), indicating the most efficient photodetection performance. Overall, moderate Cu incorporation optimizes the balance between optical absorption, charge transport, and carrier recombination, with 0.5% Cu identified as the optimum concentration for high-performance CdS photosensors. These findings provide valuable insights for the development of low-cost, high-performance CdS-based optoelectronic devices.

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INTRODUCTION

Semiconductor thin films have become indispensable materials for modern optoelectronic technologies because of their tunable electronic properties, excellent light-harvesting capability, and compatibility with low-cost fabrication processes. Among their numerous applications, photosensors have attracted considerable research interest owing to their importance in environmental monitoring, optical communication, biomedical diagnostics, industrial automation, and imaging systems, where efficient conversion of incident photons into electrical signals is essential (Peng et al., 2013; Cai et al., 2019; Ma et al., 2024). The continuous demand for high-performance photodetectors has therefore stimulated extensive efforts toward developing semiconductor materials with enhanced optical absorption, improved electrical transport, and superior photoresponse. Cadmium sulphide (CdS) is one of the most widely investigated II–VI semiconductors for optoelectronic applications due to its direct bandgap of approximately 2.42 eV, high absorption coefficient in the visible spectral region, excellent photoconductive properties, and ease of fabrication using solution-based deposition techniques (Abdul-Manaf et al., 2015; Khimani et al., 2020; Hakami, 2022). Consequently, CdS has found applications in photodetectors, solar cells, optical switches, and light-sensitive devices. Nevertheless, the practical performance of undoped CdS thin films is frequently limited by relatively high electrical resistivity, low carrier mobility, and rapid recombination of photogenerated charge carriers, leading to reduced

photocurrent generation and poor photosensor sensitivity (Halge et al., 2020). These limitations have motivated the search for effective approaches to tailor the electrical and optical properties of CdS.

Among the various modification strategies, transition-metal doping has proven to be an effective approach for improving the optoelectronic performance of CdS. Copper (Cu) is particularly attractive because its multiple oxidation states (Cu^+ and Cu^{2+}) facilitate the formation of impurity levels within the CdS band structure, thereby modifying carrier concentration and charge transport (Liu et al., 2016; Priyadarshini et al., 2022). In addition, the ionic radius of Cu^+ (0.77 $\text{\AA}$) closely matches that of Cd^{2+} (0.95 $\text{\AA}$), enabling substitutional incorporation into the CdS lattice with minimal structural distortion (Shannon, 1976; Liu et al., 2022). Previous studies have shown that Cu incorporation can improve electrical conductivity, alter the optical bandgap, suppress charge-carrier recombination, and enhance the photoresponse of CdS thin films (Hemathangam et al., 2016; Shkir et al., 2020; Priyadarshini et al., 2022). However, these improvements are highly dependent on the Cu concentration, as excessive Cu incorporation can introduce defect states, impurity scattering centres, or secondary Cu-containing phases that promote carrier recombination, reduce carrier mobility, and degrade the optical and electrical performance of CdS thin films (Göde, 2019; Liu et al., 2017).

Cu-doped CdS thin films have been fabricated using various techniques, including spin coating (Sharma et al., 2022), spray pyrolysis (Zaker et al., 2021), pulsed laser deposition

(Cai et al., 2019), successive ionic layer adsorption and reaction (Ghediya et al., 2020), co-precipitation (Pradhabhan et al., 2019), and chemical bath deposition (CBD) (Corral et al., 2018; Inthong et al., 2019). Among these techniques, CBD offers several advantages, including low processing temperature, low fabrication cost, simple experimental setup, excellent compositional control, and the ability to deposit uniform films over large substrate areas without vacuum facilities (Ali, 2022; Di Mari et al., 2024; Tomas et al., 2024). These advantages make CBD particularly suitable for scalable fabrication of semiconductor thin films intended for optoelectronic applications.

Despite the considerable number of studies on Cu-doped CdS thin films, significant knowledge gaps remain. Most previous investigations have focused primarily on structural evolution, optical characterization, or conventional electrical resistance measurements, while comprehensive analyses of electrical transport mechanisms remain relatively limited. For example, Sharma et al. (2022) demonstrated that Cu incorporation reduced the electrical resistance of CdS thin films but did not investigate Hall mobility, carrier concentration, or Hall coefficient, making it difficult to explain the underlying transport behaviour. Likewise, Inthong et al. (2019) investigated only a narrow Cu concentration range (0.1–0.4 mol%) without Hall-effect characterization, limiting understanding of how Cu concentration influences carrier transport. Furthermore, relatively few studies have simultaneously correlated Cu concentration with film thickness, surface roughness, optical properties, Hall-effect parameters, photosensitivity, and responsivity. Such an integrated analysis is essential for identifying the optimum Cu concentration capable of maximizing photosensor performance while providing a mechanistic understanding of the relationship between Cu incorporation and charge transport.

The novelty of this work lies in the comprehensive investigation of the influence of Cu concentration on chemically deposited CdS thin films by correlating thickness, surface roughness, optical properties, Hall-effect electrical transport parameters, and photosensing performance within a single study. Unlike many previous reports that relied primarily on optical characterization or simple electrical measurements, this work employs Hall-effect analysis to elucidate the relationship between Cu concentration, charge transport, and photoresponse. Cu-doped CdS thin films containing 0–2.0% (v/v) Cu were synthesized by chemical bath deposition under identical conditions, and their thickness, surface roughness, optical properties, electrical transport, photosensitivity, and responsivity were systematically evaluated to identify the optimum Cu concentration for photosensor applications.

Accordingly, Cu-doped CdS thin films with Cu concentrations of 0, 0.5, 1.0, 1.5, and 2.0% (v/v) were synthesized by chemical bath deposition while maintaining identical deposition parameters. The influence of Cu concentration on the thickness, surface roughness, optical properties, electrical transport behaviour, photosensitivity, and responsivity of the films was systematically investigated. The outcomes of this study provide a comprehensive understanding of the role of Cu concentration in optimizing the optoelectronic performance of CdS thin films for high-performance photosensor applications.

MATERIALS AND METHODS

Copper-doped cadmium sulphide (Cu) thin films were synthesized on microscope glass substrates using the chemical bath deposition (CBD) technique. Cadmium

chloride (CdCl_2), thiourea (H_2NCSNH_2), copper chloride (CuCl_2), disodium ethylenediaminetetraacetic acid (Na_4EDTA), and 25% ammonium hydroxide (NH_4OH) of analytical grade were used without further purification.

Synthesis of Cu-Doped CdS Thin Films

Solutions of 0.08 M CdCl_2 , 0.08 M thiourea, and 0.08 M CuCl_2 were prepared separately in 50 mL of deionized water. A 0.08 M Na_4EDTA solution was also prepared and used as the complexing agent. The pH of the CdCl_2 solution was adjusted to 10 by the gradual addition of NH_4OH until the initially formed $\text{Cd}(\text{OH})_2$ precipitate completely dissolved. Subsequently, 10 mL of 0.08 M EDTA and 50 mL of 0.08 M thiourea were added successively with continuous stirring to obtain a homogeneous reaction bath.

Copper doping was achieved by introducing CuCl_2 into the CdS solution at concentrations of 0, 0.5, 1.0, 1.5, and 2.0% (v/v), while maintaining all other deposition parameters constant.

Glass substrates were cleaned with acetone, rinsed thoroughly with deionized water, and dried under ambient conditions before deposition. The substrates were immersed vertically in the reaction bath before heating commenced. The bath temperature was gradually increased to 80 °C, and deposition time was measured only after the desired temperature had been attained. All films were deposited for 30 min. Following deposition, the films were removed from the bath, rinsed with deionized water to eliminate loosely adhered particles, and dried in air.

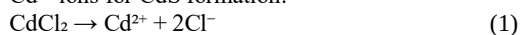
To verify the crystal structure and surface morphology of the optimized composition, X-ray diffraction (XRD) and scanning electron microscopy (SEM) analyses were performed on the selected Cu-doped CdS samples.

Ohmic contacts for electrical characterization were fabricated using conductive graphite paste prepared from graphite powder and commercial nail hardener. Current–voltage (I–V) measurements were performed under dark and illuminated conditions.

Chemical Reactions Involved in the Preparation of CdS and Cu-Doped CdS Thin Films

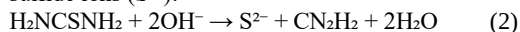
i. Dissociation of Cadmium Chloride (CdCl_2)

Cadmium chloride dissociates in aqueous solution to provide Cd^{2+} ions for CdS formation:



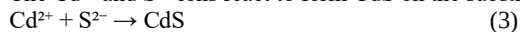
ii. Decomposition of Thiourea

In the alkaline medium, thiourea decomposes to produce sulfide ions (S^{2-}):



iii. Formation of Cadmium Sulfide (CdS)

The Cd^{2+} and S^{2-} ions react to form CdS on the substrate:



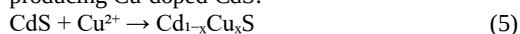
(Ja'afaru et al., 2026).

iv. Dissociation of Copper Chloride and Incorporation of Copper

Copper chloride dissolves in the reaction solution to release Cu^{2+} and Cl^- ions.



The Cu^{2+} ions are incorporated into the CdS structure, producing Cu-doped CdS:



(Where x represents the Cu concentration)

Characterization

Film thickness and surface roughness were measured using a Veeco Dektak 150 surface profilometer. For thickness measurement, the stylus was scanned across the step between

the coated and uncoated regions of the substrate. The thickness was determined from the vertical height difference between the film surface and the exposed substrate. Multiple scans were performed at different positions on each film, and a representative scan with a clear and stable profile was selected for reporting. Since the reported values were obtained from representative scans rather than statistically averaged independent measurements, no standard deviation or uncertainty is reported.

The optical properties of the films were measured using a Filmetrics F10-RT UV-Vis spectrophotometer over the wavelength range of 250–1100 nm. An uncoated glass substrate was used as the reference to account for the substrate contribution. The absorbance, reflectance, and transmittance spectra were obtained from the measurements. The corresponding optical parameters were subsequently calculated using the following equations:

$$\text{Absorption coefficient: } \alpha = \frac{\ln(1/T)}{t} \quad (6)$$

The optical band gap E_g was determined using the Tauc relation:

$$(\alpha h\nu)^2 = K(h\nu - E_g) \quad (7)$$

The approximately linear portion near the absorption edge was fitted by linear regression, and the intercept of the extrapolated linear portion with the photon-energy axis was taken as the optical band gap, E_g .

The same fitting procedure and transition assumption were applied consistently to all films.

$$\text{Refractive index: } \eta = \frac{1+\sqrt{R}}{1-\sqrt{R}} \quad (8)$$

$$\text{Extinction coefficient: } k = \frac{\alpha\lambda}{4\pi} \quad (9)$$

$$\text{Real dielectric constant: } \epsilon_r = \eta^2 - k^2 \quad (10)$$

$$\text{Imaginary dielectric constant: } \epsilon_i = 2\eta k \quad (11)$$

$$\text{Optical conductivity: } \sigma_0 = \frac{k\eta c}{\lambda} \quad (12)$$

Where T = transmittance and t = the thickness of the material, R = reflectance, and $h\nu$ = photon energy

(E. Otth et al., 2011; Abdullah et al., 2021; Hirpara et al., 2022; Dutta et al., 2022; Zhou et al., 2015; Mahrov et al., 2004; Ja'afaru et al., 2026).

The electrical characteristics of the samples, including carrier concentration, Hall mobility, resistivity, and average Hall coefficient, were measured using an ECOPIA Hall Effect Measurement System (HMS-3000) at room temperature (300 K). Current-voltage (I-V) measurements were performed

with a Keithley 2400 SourceMeter under both dark and illuminated conditions. Illumination was provided by a Newport Oriel Solar Simulator operating under the AM 1.5G standard spectrum, with a light intensity of 100 mW cm⁻² over a wavelength range of 300–1400 nm. The electrical response obtained under these conditions was used to evaluate the photosensitivity and responsivity of the samples. The relevant parameters were calculated using the following equations:

$$\text{Photosensitivity } S(\%) = \frac{I_{\text{Light}} - I_{\text{Dark}}}{I_{\text{Dark}}} \times 100 \quad (13)$$

$$\text{Responsivity } R = \frac{I_{ph}(A)}{E(W/cm^2) A(cm^2)} = \frac{I_{ph}(A)}{P_{inc}(W)} \quad (14)$$

Where I_{Light} and I_{Dark} denote the photocurrent and dark current, respectively, and P_{inc} = incident optical power (Ja'afaru et al., 2026).

X-ray diffraction (XRD) analysis was performed on the unannealed 0.5% Cu-doped CdS thin film using a Tonda TD-3500 diffractometer with CuK α radiation ($\lambda = 1.5406 \text{ \AA}$) to investigate its crystal structure and phase composition. The structural parameters were then determined from the XRD data using the following equations:

$$\text{Crystallite size: } D = \frac{K\lambda}{\beta \cos\theta} \quad (15)$$

$$\text{Estimated Dislocation density: } \rho = \frac{1}{D^2} \quad (16)$$

$$\text{Microstrain: } \epsilon = \frac{\beta}{4 \tan\theta} \quad (17)$$

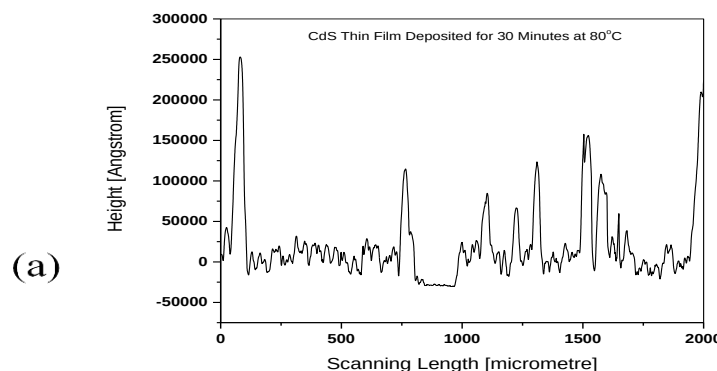
Where K = Scherrer constant, β = FWHM and θ = Bragg angle (Mahrov et al., 2004; Patterson et al., 2016; Gadallah et al., 2013)

The surface morphology of the unannealed 2% Cu-doped CdS (CuCdS) thin film was characterized using a ZEISS EVO MA 10 Scanning Electron Microscope (SEM).

RESULTS AND DISCUSSION

Effect of Cu Concentration on Film Thickness and Surface Topography and Roughness

Figure 1 presents the stylus surface profiles of the undoped and Cu-doped CdS thin films. The corresponding numerical values are summarized in Table 1, while the variation of thickness and roughness with Cu concentration is illustrated in Figures 2 and 3, respectively. The surface profiles reveal that Cu incorporation significantly modifies the topography and growth behaviour of CdS thin films deposited by the chemical bath deposition method.



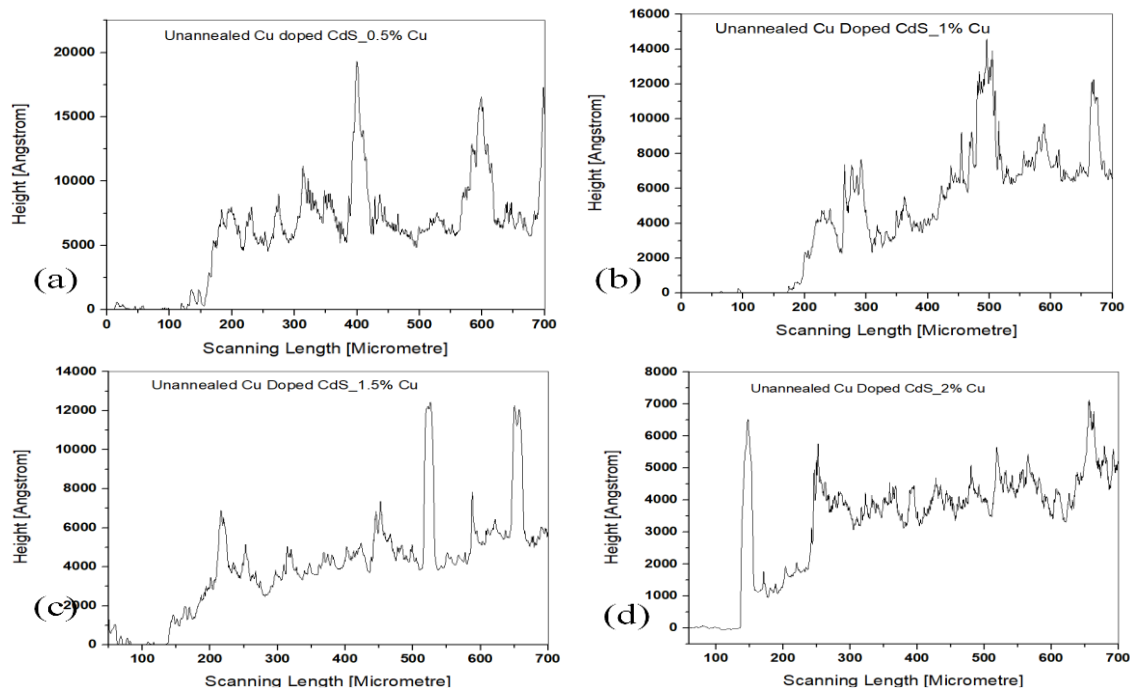


Figure 1: Plot of Surface Profiles of Cu Doped CdS Samples

Table 1: Thickness and Average Roughness R_a (Nanometer) of Cu Doped CdS Samples

Thickness and Average Roughness		
Concentration of Cu dopant [% in Volume]	Cu Doped CdS Thickness (micrometer)	Cu Doped CdS Average Roughness (Nanometer)
0.0	3.0	3029.20
0.5	0.6	204.24
1.0	0.5	142.85
1.5	0.4	102.37
2.0	0.38	67.17

The undoped CdS film (0% Cu) exhibits a highly irregular surface profile characterized by large height fluctuations and numerous sharp peaks distributed along the scan length (Figure 1a). This morphology corresponds to the highest film thickness (3.0 μm) and surface roughness (3029.20 nm) shown in Table 1 and is consistent with the trends presented in Figures 2 and 3. The pronounced surface irregularities indicate substantial variation in the surface topography of the undoped film.

Upon introducing 0.5% Cu, the surface profile becomes considerably smoother, with reduced peak heights and a more uniform height distribution (Figure 1b). This change is accompanied by a sharp decrease in film thickness to 0.60 μm (Figure 2) and a substantial reduction in surface roughness to 204.24 nm (Figure 3). The observed changes indicate that Cu incorporation alters the surface morphology and growth behaviour of the deposited CdS films. Similar changes in film morphology with Cu incorporation have been reported by Inthong et al. (2019) and Sharma et al. (2022).

Further increasing the Cu concentration to 1.0% and 1.5% produces progressively smoother surface profiles (Figures 1c and 1d). Although isolated peaks remain visible, the overall height variation becomes considerably smaller. Correspondingly, the film thickness decreases to 0.50 and 0.40 μm (Figure 2), while the average roughness decreases to

142.85 and 102.37 nm (Figure 3). These results demonstrate a progressive modification of the surface topography with increasing Cu concentration, as evidenced by the reduction in both film thickness and surface roughness.

At 2.0% Cu, the surface profile exhibits the smallest height variation among all the samples (Figure 1e), corresponding to the minimum thickness of 0.38 μm (Figure 2) and the lowest average roughness of 67.17 nm (Figure 3). This indicates that the highest Cu concentration investigated produces the smoothest surface among the deposited films. However, the reduction in surface roughness does not necessarily imply a corresponding reduction in electrically active defects or an improvement in charge transport. This is evident from the fact that the 2.0% Cu film did not exhibit the highest Hall mobility or photosensing performance. Therefore, the electrical and photosensing results should be considered alongside the surface morphology when evaluating the overall effect of Cu incorporation.

Overall, the surface profile analysis demonstrates a progressive change in the surface morphology of chemically deposited CdS films with increasing Cu concentration. As shown in Figures 2 and 3, increasing Cu concentration results in a progressive reduction in both film thickness and surface roughness, producing smoother surface profiles.

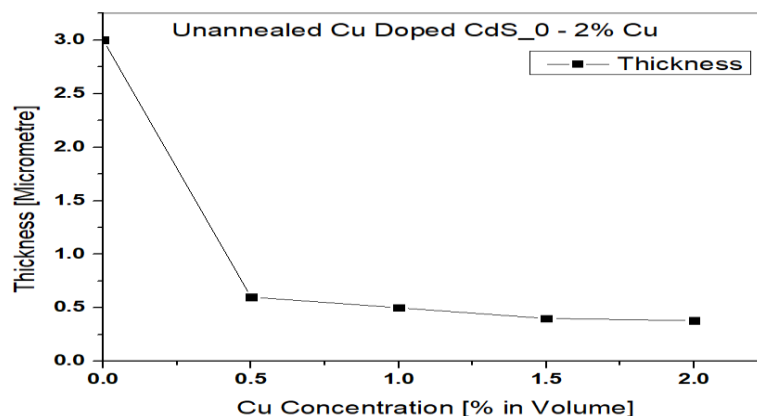


Figure 2: A Plot of Thickness against Cu Concentration

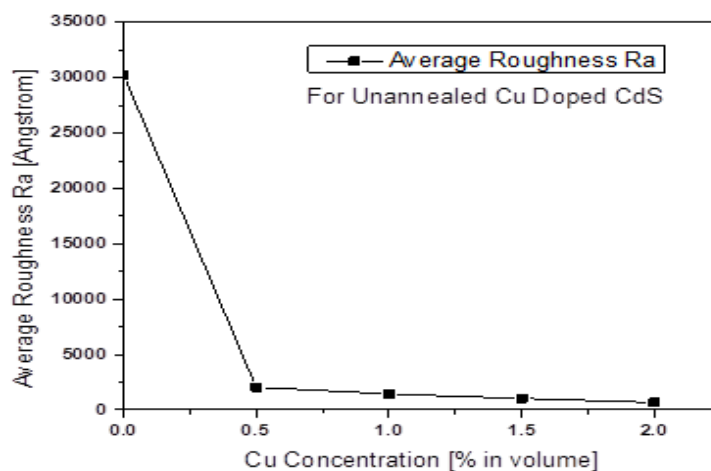


Figure 3: A Plot of Average Roughness against Cu Concentration.

Effect of Cu Concentration on Optical Properties of Cu Doped CdS Thin Films

Absorption Coefficient

The absorption coefficient spectra as presented in figure 4 demonstrate that Cu incorporation significantly enhanced the optical absorption of CdS thin films, particularly within the ultraviolet and visible regions. The undoped CdS film exhibited the lowest maximum absorption coefficient of $5.89 \times 10^3 \text{ cm}^{-1}$, whereas the 2.0% Cu-doped film reached $8.50 \times 10^4 \text{ cm}^{-1}$, representing an increase of more than one order of magnitude. It is observed that increased in Cu concentration enhances light interaction in the UV range. A similar enhancement was observed in the visible region, where the maximum absorption coefficient increased from $9.91 \times 10^3 \text{ cm}^{-1}$ for undoped CdS to $6.50 \times 10^4 \text{ cm}^{-1}$ for the 2.0% Cu-doped film. The higher absorption coefficients indicate that Cu doping substantially improves the interaction between incident photons and the CdS lattice.

The enhancement is attributed to the incorporation of Cu ions into the CdS crystal lattice, which introduces localized impurity levels within the band structure and increases the probability of electronic transitions following photon absorption. In addition, Cu-induced defect states broaden the absorption edge, allowing more photons to participate in carrier generation. Similar improvements in optical

absorption following Cu incorporation have been reported by Sharma et al. (2022), Priyadarshini et al. (2022), and Corral et al. (2018), who attributed the increase to modifications in the electronic structure and enhanced light-matter interaction.

Although the 2.0% Cu-doped film exhibited the highest absorption coefficient, it did not produce the highest photosensitivity or responsivity. This indicates that optical absorption alone does not determine photosensor performance. At higher Cu concentrations, defect-assisted recombination is likely to increase, reducing the number of photogenerated carriers available for electrical conduction. Consequently, optimum photosensor performance requires a balance between efficient photon absorption and effective carrier transport. This interpretation is consistent with Hall-effect measurements, which showed that the highest carrier mobility was achieved at 1.5% Cu rather than 2.0% Cu, suggesting that excessive Cu incorporation introduces defect states that offset the benefits of enhanced optical absorption. Similar observations have been reported by Göde (2019) and Liu et al. (2017), who demonstrated that excessive Cu incorporation can generate defect states that increase carrier scattering and recombination, thereby limiting the optoelectronic performance of CdS thin films.

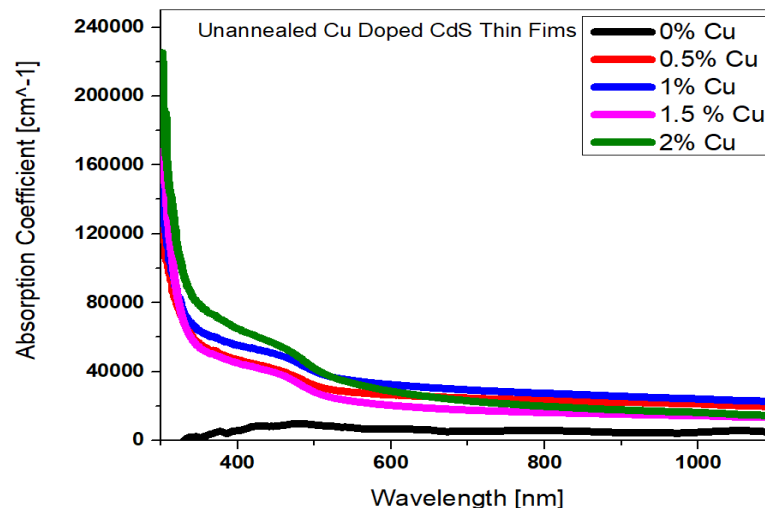


Figure 4: A Plot of Absorption Coefficient of Unannealed Cu Doped CdS Samples against Wavelength

Optical Bandgap

The optical bandgap of the Cu-doped CdS thin films increased from 2.07 eV for the undoped film to a maximum of 2.31 eV at 1.5% Cu, followed by a slight decrease to 2.27 eV at 2.0% Cu, as illustrated in Figure 5 and Table 2. The variation in bandgap indicates that Cu incorporation modifies the optical and electronic properties of the CdS films. The observed bandgap widening may be associated with changes in the electronic structure and defect characteristics of the films resulting from Cu incorporation. Although the Burstein–Moss effect can contribute to bandgap widening through increased carrier concentration, the relatively low and non-monotonic Hall carrier concentrations obtained in this study do not provide sufficient evidence to attribute the observed bandgap variation solely to the Burstein–Moss effect. Cu incorporation may also modify the local crystal potential and electronic states, thereby influencing the optical transition energy. Similar variations in the optical bandgap of

Cu-doped CdS thin films have been reported by Hemathangam et al. (2016), Sharma et al. (2022), Priyadarshini et al. (2022), and Göde (2019).

The slight reduction in bandgap observed at 2.0% Cu may be associated with changes in the defect and electronic structure of the films at higher Cu concentration. The introduction of additional localized states or increased structural disorder may influence the optical absorption edge and contribute to the observed reduction in bandgap. Similar behaviour has been reported by Liu et al. (2017) and Göde (2019) for Cu-doped CdS films at higher Cu concentrations.

The ability to tune the optical bandgap through controlled Cu incorporation is relevant to visible-light photodetector applications because changes in the absorption edge can influence the spectral range of optical response. The present results show that Cu incorporation modifies the optical bandgap of CdS, with the largest measured bandgap occurring at 1.5% Cu.

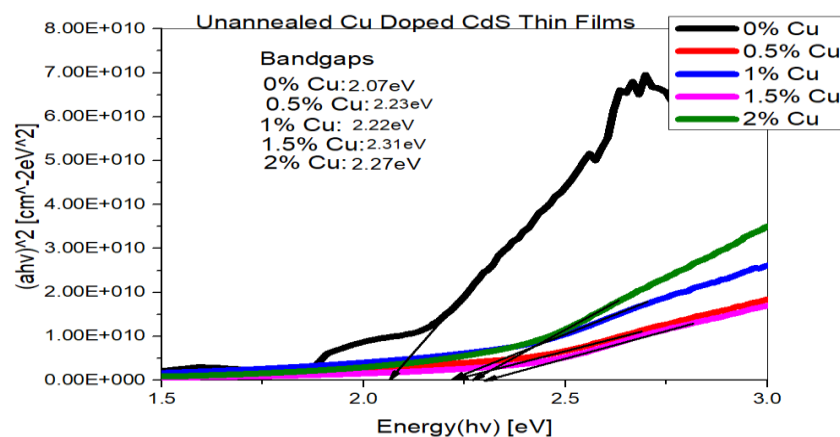


Figure 5: A Plot of $(\alpha h\nu)^2$ against $h\nu$ of Unannealed Cu Doped CdS Samples

Table 2: Energy Bandgaps of Unannealed Cu Doped CdS Samples

Energy Bandgaps (eV)	
Concentration of Cu-dopant [% v/v]	Unannealed Cu Doped CdS
0.0	2.07
0.5	2.23
1.0	2.22
1.5	2.31
2.0	2.27

Extinction Coefficient

Figure 6 shows that the extinction coefficient increased substantially following Cu incorporation. In both the ultraviolet and visible regions, the 2.0% Cu-doped film exhibited the highest extinction coefficient, while the undoped CdS film consistently recorded the lowest values. Beyond approximately 500 nm, the 1.0% Cu film maintained the highest extinction coefficient throughout the visible and near-infrared regions.

The extinction coefficient represents the attenuation of electromagnetic waves within the semiconductor and is directly related to optical absorption. The observed increase therefore confirms the enhanced photon absorption produced

by Cu incorporation. The higher extinction coefficient indicates increased interaction between incident light and charge carriers resulting from Cu-induced modifications of the electronic structure.

Comparable increases in extinction coefficient have been reported for transition-metal-doped CdS thin films, where impurity incorporation increased optical attenuation through enhanced electronic transitions and stronger photon–electron coupling.

The sustained extinction coefficient observed for the 1.0% Cu film over a broad wavelength range suggests improved broadband optical response, making this concentration particularly attractive for visible-light photodetection.

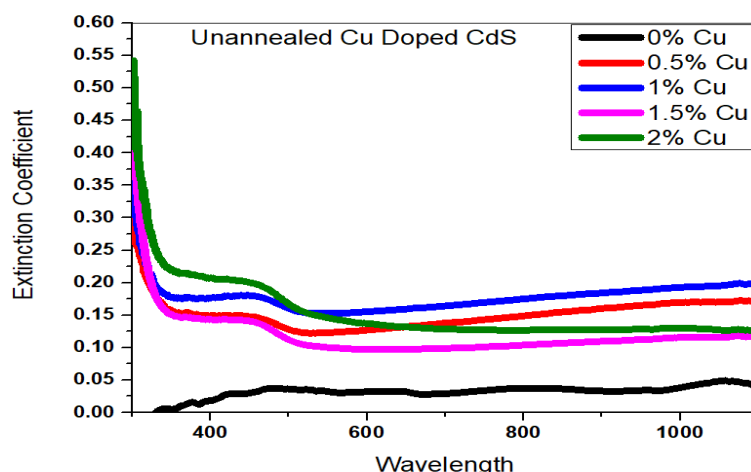


Figure 6: A Plot of Extinction Coefficient of Unannealed Cu Doped CdS Samples against Wavelength.

Refractive Index

Figure 7 shows the variation of the refractive index of unannealed Cu-doped CdS thin films as a function of wavelength. The refractive index of all samples increased with increasing wavelength, although the magnitude and rate of increase depended strongly on the Cu concentration. The undoped, 0.5% Cu, and 1.0% Cu films exhibited relatively low refractive indices in the shorter wavelength region, increasing gradually from approximately 1.0 at 500 nm to about 2.49 near 1100 nm. This gradual increase indicates enhanced electronic polarization as the wavelength increases. In contrast, the 1.5% and 2.0% Cu-doped films exhibited a much steeper increase in refractive index immediately above 500 nm. The 1.5% Cu film attained the highest refractive index of approximately 2.64 at around 600–650 nm, while the 2.0% Cu film reached a slightly lower maximum value of approximately 2.63 at around 650–700 nm. Beyond their peak values, both films showed a slight gradual decrease in refractive index towards longer wavelengths before converging with the other samples at approximately 2.50 near 1100 nm.

The enhancement in refractive index with Cu incorporation indicates an increase in the optical density and electronic polarizability of the CdS films. Copper atoms introduce localized electronic states within the CdS lattice, increasing the interaction between incident electromagnetic radiation

and bound electrons. This stronger interaction results in a higher refractive index, particularly at moderate Cu concentrations. The slight decrease observed after the maximum values for the 1.5% and 2.0% Cu-doped films is characteristic of normal optical dispersion, where the refractive index decreases gradually as the photon energy becomes insufficient to sustain strong electronic transitions. Among all the investigated compositions, the 1.5% Cu-doped film exhibited the highest refractive index of approximately 2.64, suggesting that this concentration provides the greatest enhancement in optical polarization. Increasing the Cu concentration to 2.0% did not produce a further increase in the maximum refractive index, indicating that the beneficial effect of Cu incorporation approaches saturation at higher dopant concentrations. This behaviour may be attributed to the introduction of additional defect states that partially offset the increase in polarization.

Overall, the refractive index results demonstrate that moderate Cu incorporation significantly improves the optical density of CdS thin films, with the 1.5% Cu-doped film exhibiting the optimum optical response. The higher refractive index is advantageous for optoelectronic and photosensor applications because it enhances light confinement within the semiconductor, thereby improving light–matter interaction and potentially increasing device efficiency.

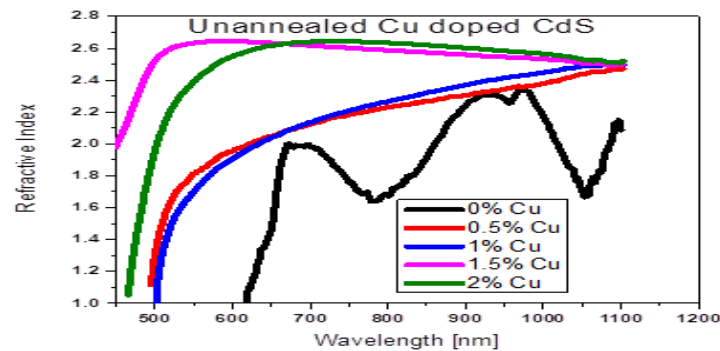


Figure 7: A Plot of Refractive Index of Unannealed Cu Doped CdS Samples against Wavelength.

Real Dielectric Constant

Figure 8 shows that the real dielectric constant increased progressively with increasing wavelength for all Cu concentrations. The 1.5% Cu-doped film exhibited the highest dielectric constant within the visible region, while the 2.0% Cu film reached the largest values in the near-infrared region.

The real dielectric constant represents the ability of a material to store electrical energy under an applied electromagnetic

field. Its increase with Cu concentration suggests enhanced electronic polarization resulting from increased free-carrier interaction and stronger lattice polarization. Similar increases in dielectric constant have been observed in Cu-doped CdS and other transition-metal-doped II–VI semiconductors.

The enhanced dielectric response indicates improved interaction between electromagnetic radiation and the semiconductor, which is beneficial for photodetectors operating under varying illumination conditions.

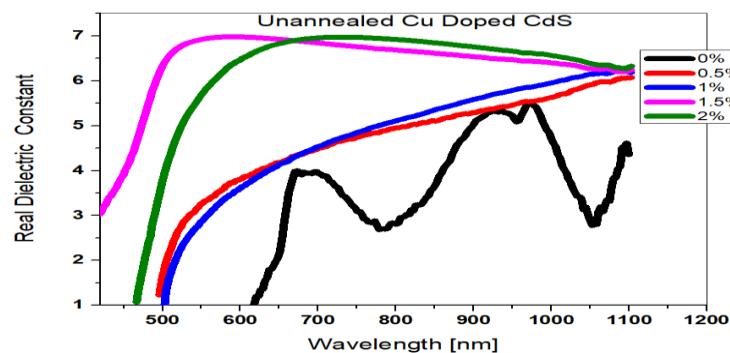


Figure 8: A Plot of Real Dielectric Constant of Unannealed Cu Doped CdS Samples against Wavelength.

Imaginary Dielectric Constant

The imaginary dielectric constant increased with Cu incorporation, particularly for the 1.0% and 1.5% Cu films, indicating greater optical energy dissipation associated with photon absorption. In contrast, the 2.0% Cu film exhibited an initial sharp increase followed by stabilization across the near-infrared region as shown in figure 9.

The imaginary dielectric constant is associated with optical loss and carrier excitation. The observed increase reflects

enhanced interband electronic transitions resulting from Cu-induced impurity states. However, excessive Cu concentrations appear to introduce additional scattering centres that stabilize the dielectric response despite stronger optical absorption.

These results suggest that moderate Cu concentrations maximize useful optical transitions, whereas excessive Cu incorporation increases defect-assisted energy dissipation.

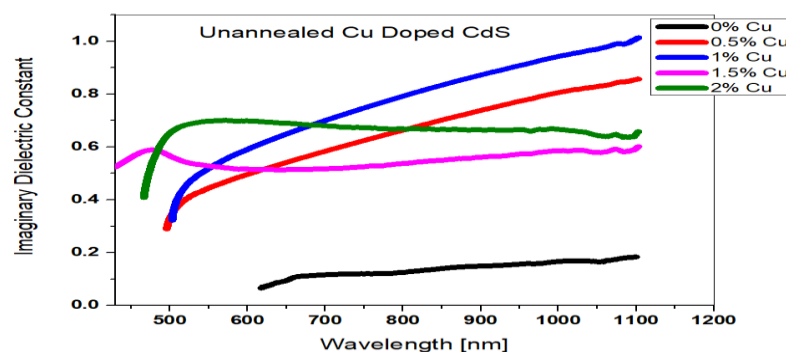


Figure 9: A Plot of Imaginary Dielectric Constant of Unannealed Cu Doped CdS Samples against Wavelength

Optical Conductivity

Figure 10 illustrates the optical conductivity spectra of the undoped and Cu-doped CdS thin films. The calculated optical conductivity increased markedly with Cu incorporation, reaching a maximum value of $5.41 \times 10^{10} \text{ s}^{-1}$ at 1.5% Cu, compared with $4.66 \times 10^9 \text{ s}^{-1}$ for the undoped CdS film. A slight reduction to $4.92 \times 10^{10} \text{ s}^{-1}$ was observed at 2.0% Cu, although the value remained substantially higher than that of the undoped film.

The observed variation in optical conductivity is associated with changes in the optical response of the films following Cu incorporation. The increase up to 1.5% Cu indicates enhanced interaction of the films with incident radiation and changes in their electronic response. The slight decrease at 2.0% Cu may be associated with changes in the film composition and electronic structure at the higher Cu concentration. However, the optical conductivity calculated from the optical constants should not be interpreted as a direct measurement of DC carrier transport.

The optical conductivity trend shows similar concentration dependence to the Hall-effect results, with both parameters reaching their highest values at 1.5% Cu. This similarity suggests that Cu incorporation produces concurrent changes in the optical and electrical properties of the films. Nevertheless, the optical conductivity and Hall measurements represent different physical responses and should therefore be considered as complementary rather than equivalent measures of charge transport.

Overall, the optical characterization demonstrates that Cu incorporation significantly modifies the optoelectronic response of the CdS thin films. The maximum calculated optical conductivity at 1.5% Cu, together with the corresponding Hall and photosensing results, indicates that this composition exhibits notable changes in both optical and electrical characteristics. The observed trends demonstrate that the effect of Cu incorporation cannot be assessed from optical conductivity alone, but should be considered together with the independent electrical and photosensing measurements.

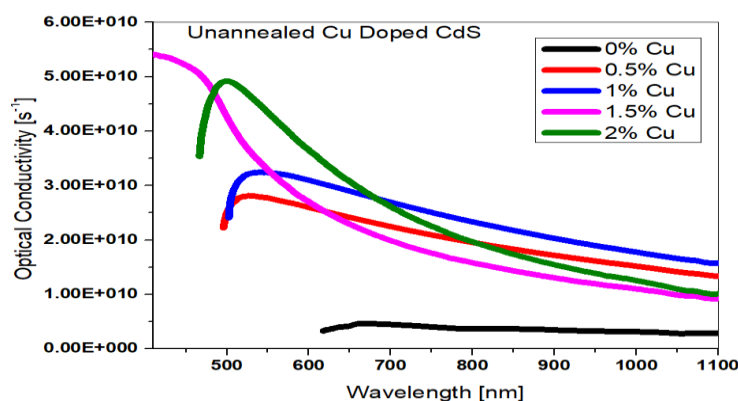


Figure 10: A Plot of Optical Conductivity of Unannealed Cu Doped CdS Samples against Wavelength.

Effect of Cu Concentration on Hall-Effect Electrical Properties

Table 3: Electrical Properties of Unannealed Cu Doped CdS Thin Films from Hall Measurement.

Cu Concentration (% in volume)	Bulk Concentration ($/\text{cm}^3$)	Hall Mobility (cm^2/Vs)	Resistivity (Ωcm)	Average Hall Coefficient (cm^3/C)
0.0	-2.662E+11	3.539E+02	6.625E+04	-2.345E+07
0.5	-3.768E+11	3.518E+02	4.709E+04	-1.657E+07
1.0	-1.495E+11	1.167E+03	3.579E+04	-4.176E+07
1.5	-2.316E+11	1.808E+03	1.491E+04	-2.695E+07
2.0	-2.779E+11	1.001E+03	2.243E+04	-2.246E+07

Hall-effect measurements confirmed that all Cu-doped CdS thin films retained n-type conductivity, as indicated by the negative Hall coefficients (Table 3). The carrier concentration varied non-linearly with Cu concentration, increasing initially from $2.66 \times 10^{11} \text{ cm}^{-3}$ for undoped CdS to $3.77 \times 10^{11} \text{ cm}^{-3}$ at 0.5% Cu, before decreasing at 1.0% Cu and increasing slightly at higher concentrations. This behaviour indicates that Cu incorporation affects the carrier concentration of the CdS films. The non-linear variation may be associated with changes in the electronic and defect-related characteristics of the films; however, the specific defect states responsible cannot be established from the Hall measurements alone.

A remarkable enhancement in Hall mobility was observed with Cu incorporation. The mobility increased from $3.54 \times 10^2 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ for undoped CdS to a maximum of $1.81 \times 10^3 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ at 1.5% Cu, before declining to $1.00 \times 10^3 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ at 2.0% Cu. The increase in mobility may be associated with changes in the structural and morphological

characteristics of the films. However, the specific contribution of grain-boundary scattering or surface defects to the observed mobility variation cannot be established from the present measurements alone. The decrease in mobility at 2.0% Cu may be associated with increased carrier scattering at higher Cu concentrations, although the specific scattering mechanisms were not directly investigated. Similar trends have been reported for Cu-doped CdS thin films by Sharma et al. (2022) and Liu et al. (2022).

The improvement in carrier mobility resulted in a substantial reduction in resistivity from $6.63 \times 10^4 \Omega \text{ cm}$ for undoped CdS to $1.49 \times 10^4 \Omega \text{ cm}$ at 1.5% Cu. The slight increase in resistivity at 2.0% Cu may be associated with the reduction in mobility and changes in carrier transport at the higher Cu concentration. Interestingly, the maximum Hall mobility at 1.5% Cu occurred at the same Cu concentration as the maximum calculated optical conductivity. The two measurements therefore show similar concentration

dependence, although they represent different physical responses. Nevertheless, this concentration did not produce the highest photosensitivity, indicating that the photoresponse depends on factors beyond carrier transport, including the optical and photoelectrical characteristics of the films.

Overall, the Hall-effect results show that the 1.5% Cu film exhibited the highest mobility and lowest resistivity among the investigated compositions.

Effect of Cu Concentration on Photosensing Performance of Cu Doped CdS Thin Films

The I-V results as shown in figure 11 and for unannealed Cu-doped CdS thin films show that undoped CdS (a) exhibits the highest light current (1.82×10^{-6} A) and low dark current (5.67×10^{-8} A), indicating good photosensitivity. Doping with

0.5% Cu (b) significantly increases both currents, especially the dark current, suggesting the introduction of defect states that enhance recombination. At 1.0% Cu (c), both light and dark currents drop and become nearly equal, indicating poor photosensitivity due to increased carrier trapping or structural disorder.

At 1.5% Cu (d), the dark current decreases substantially while the light current remains moderate, indicating a measurable photoresponse. At 2.0% Cu (e), the photoresponse decreases again, which may be associated with changes in phase composition and carrier transport at higher Cu concentration. The presence of Cu_2S as a secondary phase may contribute to this variation, although its specific effect on recombination was not directly investigated.

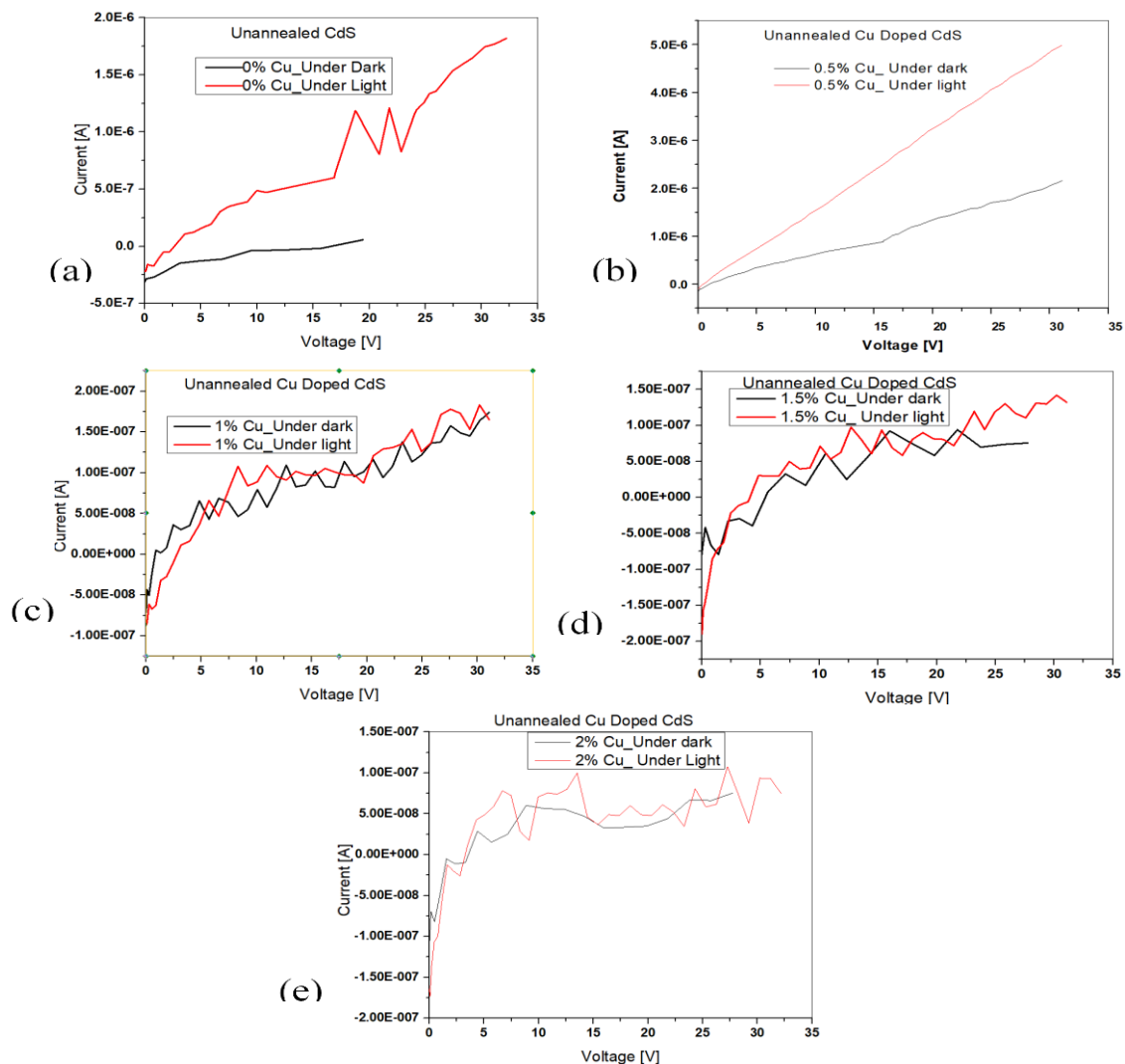


Figure 11: Plots of IV Curves (under Dark and Light Conditions) of Cu-doped CdS Samples

Table 4: Photosensitivity and Responsivity of Unannealed Cu-Doped CdS Thin Films

Cu Concentration (% v/v)	Photosensitivity (%)	Responsivity (mA/W)
0.0	3110.078	0.017633
0.5	131.0185	0.0283
1.0	5.172414	9E-05
1.5	914.2857	0.00128
2.0	43.04636	0.000325

The photosensing performance of the Cu-doped CdS thin films was evaluated in terms of photosensitivity and responsivity (Table 4). These parameters provide an assessment of the photoresponse of the films under illumination.

The photosensitivity exhibited a non-monotonic dependence on Cu concentration. The undoped CdS film showed the highest photosensitivity (3110.08%), which decreased to 131.02% at 0.5% Cu and reached a minimum of 5.17% at 1.0% Cu. A partial recovery was observed at 1.5% Cu (914.29%), followed by a further decline to 43.05% at 2.0% Cu. The exceptionally high photosensitivity of the undoped film can be associated with its very low dark current, which results in a large photocurrent-to-dark-current ratio. With Cu incorporation, the increase in electrical conductivity and carrier concentration can increase the dark current, thereby reducing the calculated photosensitivity. At 1.5% Cu, the relatively high Hall mobility may have contributed to the partial recovery in photosensitivity. The subsequent decrease at 2.0% Cu may be associated with changes in the defect and carrier-transport characteristics of the film. However, specific mechanisms involving carrier trapping and recombination cannot be established from the present measurements alone. In contrast, the responsivity followed a different trend. It increased from 0.0176 mA W⁻¹ for the undoped film to a maximum of 0.0283 mA W⁻¹ at 0.5% Cu before decreasing at higher Cu concentrations. The enhanced responsivity at 0.5% Cu indicates an improved photoresponse and may be associated with more effective generation and collection of

photogenerated carriers. This enhancement occurs alongside the changes observed in the optical and electrical properties of the Cu-doped films. Beyond 0.5% Cu, the decline in responsivity despite the changes in optical absorption may be associated with changes in carrier trapping, recombination, or transport processes. Nevertheless, these mechanisms were not directly measured in the present study and therefore should be regarded as possible explanations rather than established causes.

Structural Analysis

The XRD pattern of the unannealed 0.5% Cu-doped CdS thin film (figure 12) exhibits diffraction peaks at 2θ values of 18.21°, 23.38°, 25.08°, 26.52°, 29.32°, 32.01°, 35.37°, 40.66°, 43.90°, 52.08°, and 59.45°, which correspond to the (101), (103), (100), (002), (112), (110), (201), (110), (112)/(203), (113), and (420) crystallographic planes, respectively. Comparison with JCPDS cards 26-1116 and 96-900-8863 confirms the coexistence of Cu₂S and hexagonal CdS phases in the film.

The prominent CdS diffraction peak at 26.52°, indexed to the (002) plane, confirms that the CdS matrix retains its hexagonal wurtzite crystal structure after Cu incorporation. Additional reflections at 18.21° and 23.38° are attributed to the Cu₂S phase, indicating that Cu₂S is present as a secondary phase in addition to the CdS matrix. The simultaneous presence of CdS and Cu₂S diffraction peaks therefore suggests the formation of a mixed-phase structure.

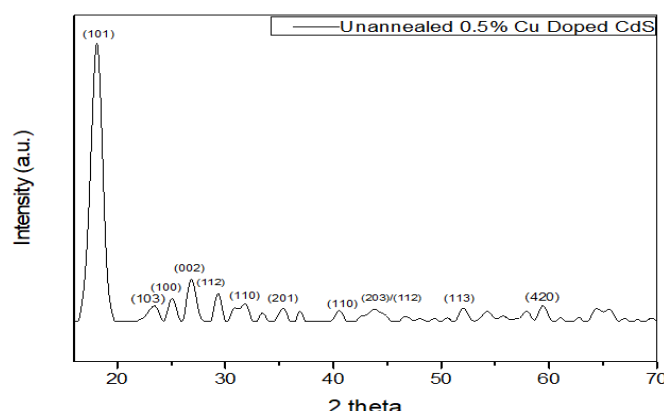


Figure 12: XRD plot for Unannealed 0.5% Cu-doped CdS Thin Films

Table 5: Microstructural Properties of Unannealed 0.5% Cu-doped CdS Thin Films

Sample	Cu (%)	Crystallite Size $D = \frac{K\lambda}{\beta \cos \theta}$ (nm)	Estimated Dislocation Density $\rho = \frac{1}{D^2}$ (nm ⁻²)	Microstrain $\epsilon = \frac{\beta}{4 \tan \theta}$
0.5% CuCdS (unannealed)	0.5	12.06	0.00687	0.0136

The relatively large number of diffraction peaks indicates that the film is polycrystalline with multiple crystallographic orientations. From the microstructural analysis (Table 5), the unannealed 0.5% Cu-doped CdS thin film has a crystallite size of 12.06 nm, an estimated dislocation density of 0.00687 nm⁻², and a microstrain of 0.0136. The moderate crystallite size and relatively low estimated dislocation density indicate good crystallinity with a comparatively low concentration of lattice defects, while the observed microstrain may be attributed to lattice distortion arising from Cu incorporation and the coexistence of CdS and Cu₂S phases.

Overall, the XRD results demonstrate that the unannealed 0.5% Cu-doped CdS thin film possesses a predominantly hexagonal CdS structure with the emergence of a secondary Cu₂S phase, confirming successful Cu incorporation while maintaining the polycrystalline nature of the CdS thin film.

Surface Morphology

The SEM micrograph of the 2% Cu-doped CdS thin film (figure 13) shows a dense and continuous surface composed of fine, closely packed grains with good substrate coverage. No obvious cracks, large voids, or pinholes are observed, indicating a uniform and well-formed film. A few localized grain clusters are visible, which may have resulted from grain coalescence during film growth. Despite these clusters, the film maintains a relatively homogeneous morphology, suggesting that 2% Cu doping promotes the formation of a compact CdS film. This observation is consistent with the surface profilometry results, which indicate improved surface uniformity. The compact and interconnected grain structure is expected to facilitate charge transport, making the film suitable for photosensor applications.

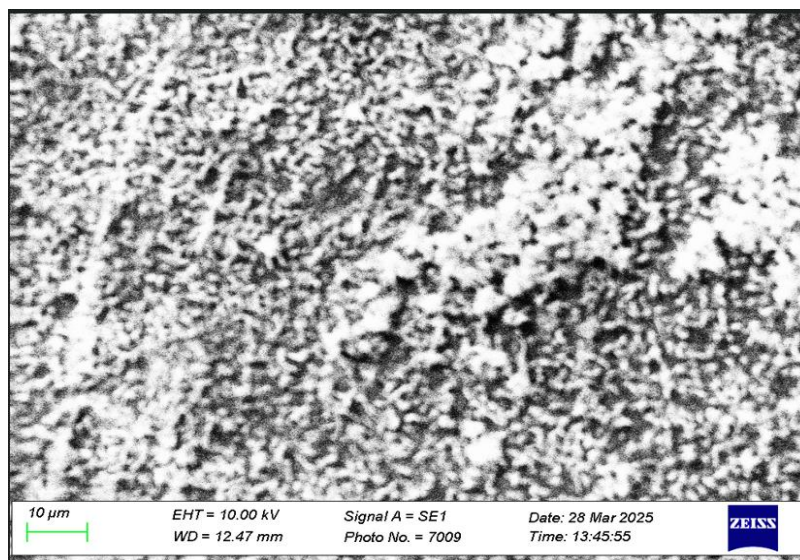


Figure 13: SEM image of 2% Cu-doped CdS (CuCdS) Thin Film

Limitations of the Study

A few limitations of the present study should be noted. First, the Cu concentrations reported for the films represent the nominal precursor concentrations used during deposition and may not correspond exactly to the actual Cu content incorporated into the films. Second, structural characterization was not performed for all Cu concentrations; therefore, a complete composition-dependent comparison of the crystalline structure could not be established. Finally, measurement uncertainty was not statistically quantified because the reported profilometric values were obtained from representative scans rather than averaged independent measurements. These limitations should be considered when interpreting the composition-dependent trends reported in this study.

CONCLUSION

Cu-doped CdS thin films containing 0–2.0% (v/v) Cu were successfully synthesized by chemical bath deposition to investigate the effect of Cu concentration on their optoelectronic and photosensing properties. Cu incorporation significantly reduced the film thickness and surface roughness while enhancing the optical absorption, optical conductivity, and electrical transport properties of the films. Hall-effect measurements confirmed n-type conductivity for all samples, with the highest Hall mobility ($1.81 \times 10^3 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$) and lowest resistivity ($1.49 \times 10^4 \Omega \text{ cm}$) obtained at 1.5% Cu. Although the undoped CdS film exhibited the highest photosensitivity (3110.08%) due to its low dark current, the 0.5% Cu-doped film achieved the highest responsivity (0.0283 mA W^{-1}), indicating the most efficient photodetection performance. Overall, the results demonstrate that moderate Cu incorporation effectively tailors the optical and electrical properties of CdS thin films, with 0.5% Cu providing the optimum balance between charge transport and photoresponse. This study highlights the potential of Cu-doped CdS thin films prepared by chemical bath deposition for low-cost, high-performance photosensor and optoelectronic applications.

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