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# Synthesis, Characterization and Study of the Optical and Solid-State Properties of Cadmium Sulfide Thin Films Deposited by Spray Pyrolysis for Optoelectronic Device Applications

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## Abstract

Cadmium sulfide (CdS) thin films were synthesized using the spray pyrolysis technique and deposited on glass substrates at controlled temperatures of 303 K, 333 K, and 363 K to investigate their optical and solid-state properties for optoelectronic device applications. Precursor solutions of cadmium nitrate tetrahydrate and thiourea were prepared in aqueous media, homogenized, and atomized onto pre-cleaned, preheated substrates, forming films through thermal decomposition. Thereafter, Optical characterization was done using UV-Vis spectrophotometry. Absorbance spectra revealed maximum absorption in the UV- visible region (280-500 nm), with the 333 K film exhibiting the highest absorbance (2.01), indicating enhanced light-harvesting capability. Refractive index analysis showed temperature dependent n - shaped dispersion profiles, with peak values of 1.625 (303 K), 2.52 (333 K), and 2.125 (363 K), reflecting variations in film compactness and electronic structure. Tauc plot analysis confirmed direct allowed electronic transitions, yielding band gap energies of 3.87 eV (303 K), 2.30 eV (333 K), and 2.41 eV (363 K). Films deposited at 333 - 363 K displayed band gap values consistent with literature and suitable for visible-light optoelectronic applications, whereas the wider band gap at 303 K suggests limited crystallinity or quantum confinement effects. The result of this study has demonstrated that substrate temperature significantly enhances the optical performance of CdS thin films prepared by spray pyrolysis, with the 333-363 K range offering the best properties for devices such as solar cells, photodetectors, and optical sensors.

**Keywords:** Cadmium Sulfide (Cds); Spray Pyrolysis; Optical Properties; Band Gap Energy; Refractive Index

## 1. Introduction

The growing global energy demand combined with limitations of fossil fuels has intensified the pursuit of renewable energy sources such as solar and wind power. Solar energy, in particular, offers a clean and abundant resource that can be efficiently converted into electricity using photovoltaic devices (Christian *et al.,* 2023). Semiconducting materials form basis in optoelectronic devices, including solar cells, photodetectors, and optical sensors. Among nanocrystalline semiconductors, Cadmium sulfide (CdS), an II-VI group semiconductor with a direct band gap of approximately 2.42 eV at room temperature(Korotcenkov, 2023), is widely recognized for its excellent optoelectronic properties, including high photosensitivity, good stability, and n-type conductivity. Considering the importance of CdS thin films in optoelectronic devices, there is needto understand how spray pyrolysis deposition conditions influence its refractive index, optical bandgap, and absorbance characteristics, informing films performance and device efficiency. CdS thin films exist in cubic or hexagonal crystal structures and serve as essential window layers in various photovoltaic devices such as CdTe and $Cu(In,Ga)Se_2$ solar cells (Powalla *et al.,* 2018). The optical and electrical properties of these films strongly depend on the deposition technique and process parameters. Various methods such as chemical bath deposition, thermal evaporation, electrodeposition, chemical vapor deposition, sputtering, and spray pyrolysis have

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been developed to fabricate CdS thin films (Ishiwu *et al.,* 2024). Among these, spray pyrolysis stands out as a simple, cost-effective, and scalable chemical deposition method capable of producing large-area, uniform, and adherent thin films with controllable thickness. It also facilitates easy doping by adding dopant precursors directly to the spray solution.

Cadmium sulfide (CdS) thin films have been extensively investigated due to their suitable optical band gap (≈2.4 eV). Yadav *et al.* (2010) demonstrated that CdS thin films deposited via spray pyrolysis exhibited polycrystalline hexagonal structures across substrate temperatures, with an optimal deposition at 300°C yielding a direct band gap of 2.44 eV and minimal electrical resistivity. The films showed n-type conductivity verified through thermoelectric power measurements. In a subsequent study, Yadav and Masumdar (2011) confirmed the n-type conductivity and reported maximum photovoltaic efficiency (0.17%) and fill factor (0.38) for films deposited at 300°C, attributed to low resistance and optimal electrical characteristics. Acosta *et al.* (2004) explored indium-doped CdS films deposited by spray pyrolysis, revealing temperature-dependent preferential crystal growth orientations (112) and (002), along with nanostructured morphology and structural defects at higher substrate temperatures. These variations correlated with shifts in the optical band gap. Abouelkhir *et al*. (2024) compared CdS films prepared by evaporation and spray pyrolysis, assessing crystallite size, lattice parameters, and optical properties such as absorbance and transmission to determine their energy gaps. Faraj *et al.* (2017) deposited CdS films on flexible polyimide substrates through spray pyrolysis, observing increasing crystallite size, surface roughness (measured by AFM), and slight band gap widening (2.42–2.48 eV) with substrate temperature increases from 300 to 375°C. Yuksel *et al.* (2013) studied hybrid solar cells incorporating CdS thin films deposited by spray pyrolysis with poly (3-hexyl) thiophene, achieving a power conversion efficiency of 0.15% and characteristic photovoltaic parameters such as short-circuit current density and open-circuit voltage. Alam *et al*. (2022) reviewed metal chalcogenide thin films, emphasizing CdS's importance in optoelectronics and solar cells. They reported CdS films prepared by chemical bath deposition exhibiting crystalline hexagonal structure confirmed by XRD, smooth morphology (RMS roughness 92 nm via AFM), and confirmed Cd and S stoichiometry through compositional analyses like EDS. These studies have confirmed that CdS thin films prepared by spray pyrolysis and related methods possess hexagonal polycrystalline structures with tunable optical band gaps around 2.4–2.5 eV, n-type conductivity, and good surface morphology. The optimal substrate temperature near 300°C often yields films with enhanced electrical and photoelectrical performance, making them suitable for various optoelectronic device applications. In this work, CdS thin films were deposited by spray pyrolysis on glass substrates, and thereafter the optical and solid-state properties examined.

## 2. Materials and Methods

The spray pyrolysis is a chemical deposition technique in which fine droplets of the desired materials to be deposited are sprayed onto preheated substrates, with films forming through thermal decomposition of the material droplets. Spray pyrolysis was used in the preparation of the cadmium sulfide (CdS) thin films. Cadmium nitrate tetrahydrate (0.274 g) was dissolved in 100 mL of distilled water to form the cadmium ion solution, while thiourea (1.22 g) was dissolved separately in 100 mL of distilled water to serve as the sulfur source. These aqueous solutions were mixed and stirred to ensure homogeneity before being loaded into the spray chamber. During deposition, glass substrates were pre-cleaned by thorough washing and ultrasonication for 30 minutes, thereafter, oven dried at 60°C to ensure cleanliness and promote film adhesion. The spray nozzle was used to atomize the precursor solution into fine droplets. These droplets were transported through compressed air onto the pre cleaned glass substrates heated to controlled temperatures of 303 K, 333 K, and 363 K. The substrate temperature was maintained to facilitate thermal decomposition of the sprayed droplets, leading to the formation of uniform CdS thin films. The spray was carried out in timed cycles with the solution sprayed intermittently, allowing solvent evaporation and chemical reaction on the hot substrate surface to deposit the CdS film progressively. At completion of the spraying cycles, the films were dried using hot air. The deposited films were subjected to optical characterization using UV-Vis spectrophotometry which revealed the films' transmittance and absorbance properties from which other parameters were determined.

## 3. Results and Discussion

The optical characterization result of the Cds films are deposited in figures 1 to 4. The spectrophotometer machine measures directly the transmission and absorbance of the sample. By using the absorbance data, all other optical parameters were calculated.

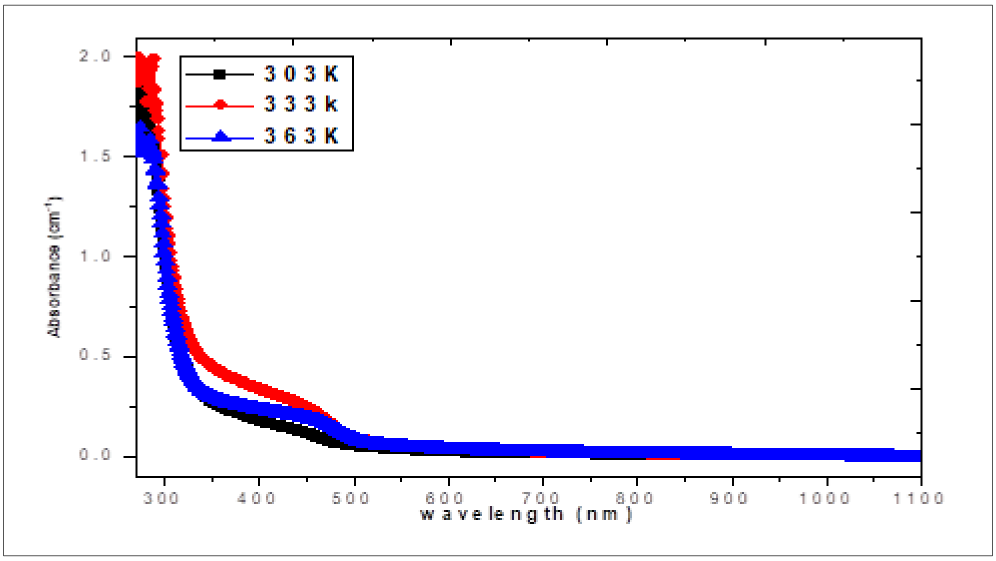


**Figure 1** Absorbance versus Wavelength curve for CdS thin films deposited at various temperatures

Figure 1 shows the absorbance spectra of CdS thin films deposited at 303 K, 333 K, and 363 K as a function of wavelength. The optical absorption coefficient (α) was calculated using the Beer-Lambert law: $\alpha = 2.303 \times (A/T)$, where A represents absorbance and T denotes film thickness.

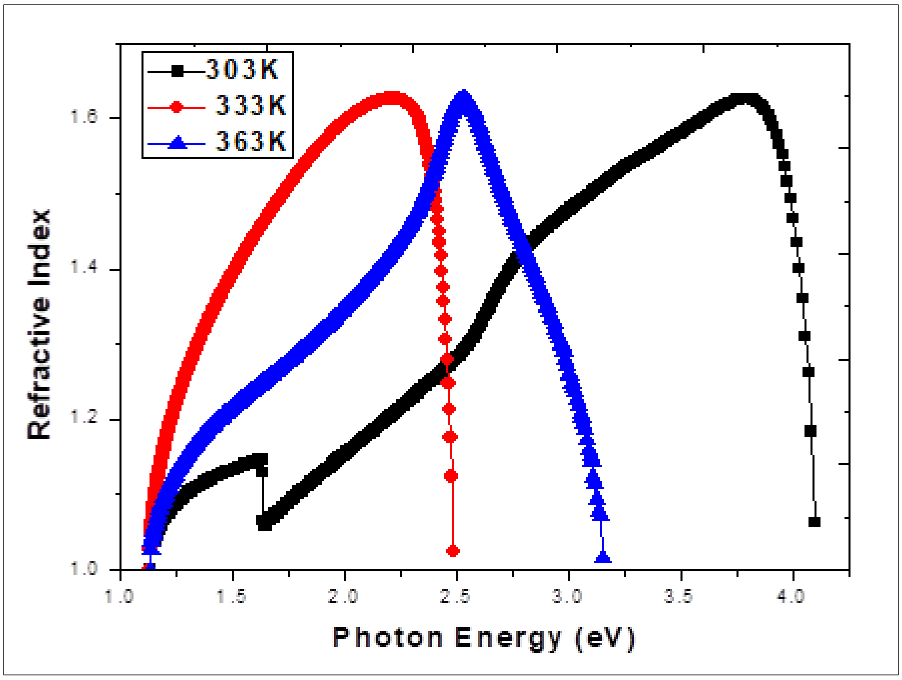


**Figure 2** Plot of Refractive index versus hv for CdS thin films deposited at 303K, 333K and 363K

The film deposited at 333 K exhibited the highest absorbance (2.01), followed by 303 K, with the lowest at 363 K (1.52). Absorbance decreased progressively with increasing wavelength across all samples, overlapping in the near-UV region and extending into the IR, with peak UV absorption (280-500 nm) indicating suitability for optoelectronic applications. This observed trend is similar to that obtained by (Hernandez-Calderon, 2018 and Abouelkhir *et al.,* 2024).

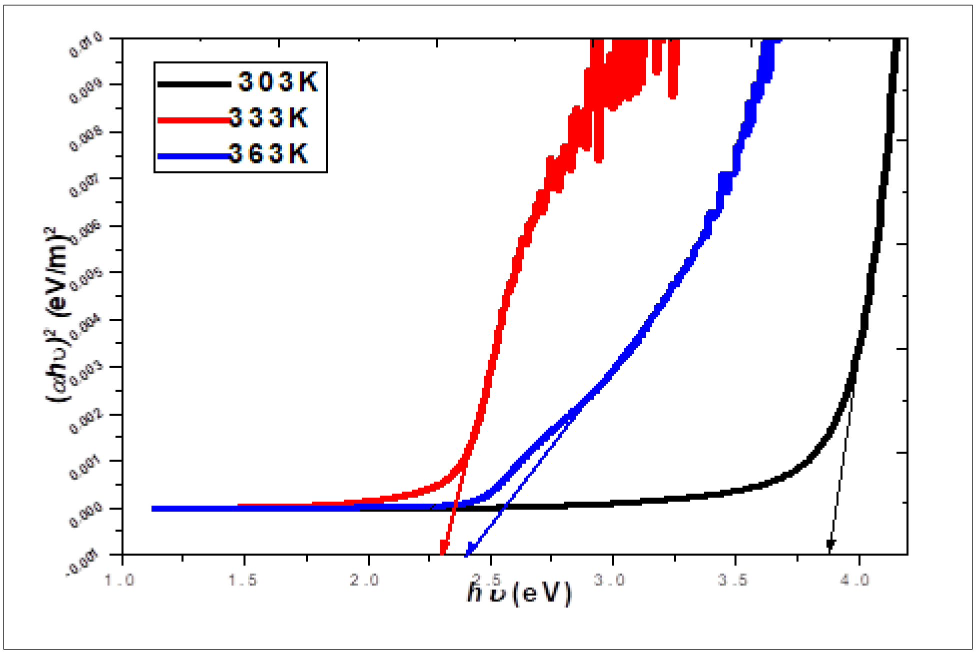


**Figure 3** Plot of $(\alpha h\nu)^2$ versus hv for CdS thin films deposited at various

The refractive index, which quantifies light bending in materials, is a factor for consideration in optical communication, device design, and spectral dispersion, with higher values causing greater light slowdown (Nworie *et al.,* 2024). Figure 2 plots refractive index versus photon energy (hν) for CdS films deposited at 303 K, 333 K, and 363 K, showing n-shaped profiles spanning 1.0 - 4.12 eV (303 K), 1.0 - 2.5 eV (333 K), and 1.0 - 3.125 eV (363 K), with peak values of 1.625 at 3.80 eV (303 K), 2.52 eV (333 K), and 2.125 eV (363 K). This is in agreement with that obtained by Agbo *et al.,* 2016 for deposition at 353k.

The CdS observed n-shaped refractive index profiles and peak positions suggest changes in the electronic band structure and film compactness with temperature, which directly influence optical performance. Higher refractive indices at specific energies indicate enhanced light-matter interaction. This is beneficial for designing efficient optoelectronic devices such as photodetectors or solar cells.

Figure 3 presents the $(\alpha h\nu)^2$ versus photon energy (hν) plot for CdS thin films, showing linear behavior near the absorption edge that confirms direct allowed band-to-band transitions. The optical band gap energy (Eg) was determined by extrapolating the linear portion to the energy axis where $(\alpha h\nu)^2 = 0$, revealing temperature-dependent values: 3.87 eV (303 K), 2.30 eV (333 K), and 2.41 eV (363 K). The Eg values for films at 333 K and 363 K align with literature reports from Yadav *et al.* (2010), Faraj *et al.* (2017), and Abouelkhir *et al.* (2024). These band gap values imply that higher deposition temperatures (333-363 K) yield CdS films with optimal ~2.4 eV band gaps suitable for visible light absorption in optoelectronic devices, while the anomalously wide 3.87 eV gap at 303 K suggests poorer crystallinity or quantum confinement effects limiting practical applications.

## 4. Conclusion

We have successfully deposited and characterized Cadmium sulfide thin films using spray pyrolysis, and the results show that substrate temperature is a major determinant of the optical and solid - state properties of CdS thin films. Films deposited at the temperature range of 333 - 363 K exhibited optimal absorbance, suitable refractive index profiles, and band gap energies (~2.3–2.4 eV) consistent with high-quality CdS required for optoelectronic applications. In contrast, the film deposited at 303 K showed a wider band gap (3.87 eV), indicating lower structural quality and reduced applicability. Our results have demonstrated that controlled deposition at moderately elevated temperatures can enhance the optical performance of CdS thin films, making the 333 - 363 K range ideal for use in devices such as solar cells, photodetectors, and optical sensors.

## Compliance with ethical standards

*Disclosure of conflict of interest*

The authors of this work have no conflicts of interest at this time

*Data Availability Statement*

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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