



Investigation of Optical and Electrical Properties of Thin Film Semiconductor Materials

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Abstract

Thin-film semiconductors are central to photovoltaic cells, transparent electronics, photodetectors, displays, and sensor platforms because their optical absorption, band-gap energy, charge transport, and electrical resistivity can be tuned through material choice, thickness, deposition conditions, doping, and post-deposition treatment. This methodology paper presents a compact experimental framework for investigating the coupled optical and electrical properties of representative thin-film semiconductor materials, with zinc oxide (ZnO), cadmium sulfide (CdS), and cadmium telluride (CdTe) used as model systems. The proposed workflow integrates controlled deposition, thickness verification, UV-Visible spectrophotometry, optical-band-gap estimation through the Tauc approach, refractive-index/thickness analysis through the Swanepoel method where interference fringes are available, and four-point-probe measurement of sheet resistance and resistivity. X-ray diffraction and surface microscopy are included as supporting checks because structural disorder and grain development can influence both photon absorption and carrier transport. The literature review is restricted to work published in 2018 or earlier. The expected outcome is a reproducible relationship among film thickness, visible transmittance, absorption edge, optical band gap, sheet resistance, and resistivity. The framework is suitable for comparative screening of thin-film materials before device fabrication and emphasizes transparent reporting of measurement conditions and uncertainty.

Introduction

Semiconductor thin films provide a functional bridge between bulk materials and nanoscale devices. Their thickness commonly ranges from a few nanometers to several micrometers, allowing the electrical and optical response to be engineered without using large quantities of material. In optoelectronic systems, a thin film may serve as a transparent conducting layer, a window layer, an absorber, a carrier-selective contact, or an active sensing medium. Because these functions place simultaneous demands on transparency, absorption, band alignment, and charge transport, optical and electrical

properties should be studied together rather than as independent characteristics.

The optical response of a semiconductor film is typically evaluated from wavelength-dependent transmission, reflection, and absorption. A key derived property is the optical band gap, which is frequently estimated from the absorption edge using the Tauc formalism. The original work of Tauc, Grigorovici, and Vancu established a widely used relationship between absorption and photon energy for amorphous semiconductors [1]. For films that show interference fringes, the transmission-envelope method developed by

Swanepoel permits the refractive index, absorption coefficient, and thickness to be extracted from a single optical spectrum [2]. These methods remain important because they transform readily measured spectrophotometric data into parameters that are directly relevant to device design.

Electrical performance is commonly summarized through sheet resistance and resistivity. Four-point measurements reduce the influence of contact resistance compared with two-terminal methods, and correction procedures for thin samples were established by Smits [3]. In transparent conducting semiconductors, the key engineering challenge is achieving sufficiently high electrical conductivity without sacrificing optical transmission. Reviews of transparent amorphous oxide semiconductors and high-mobility transparent conducting oxides have shown how mobility, carrier concentration, disorder, and deposition conditions determine this optical-electrical trade-off [4,5]. More recent work up to 2018 continued to emphasize this coupling, especially in ZnO-based transparent conductors [11].

The present paper therefore proposes a stepwise methodology for investigating thin-film semiconductor materials using ZnO, CdS, and CdTe as representative model systems. ZnO represents a wide-band-gap oxide semiconductor used in transparent electronics; CdS is a widely studied II-VI semiconductor commonly used as a window or transport layer; and CdTe represents a narrower-band-gap absorber. The goal is not to claim new experimental measurements, but to define a research-ready protocol and show literature-aligned validation targets that can be replaced by actual laboratory data when the experiment is performed.

Literature Review

The Tauc method remains one of the most widely adopted approaches for estimating the optical gap from absorption data. For a direct allowed transition, the quantity $(\alpha h\nu)^2$ is plotted against photon energy $h\nu$ and the linear region is extrapolated to the energy axis. For indirect transitions, a different exponent is used. The method should be applied only after the absorption coefficient is calculated carefully and after the transition type is justified; otherwise, the extracted band gap can become a fitting artifact. The historical basis for this analysis comes from the optical-absorption work of Tauc et al. [1].

For transparent or weakly absorbing films deposited on transparent substrates, spectral interference can contain additional information. Swanepoel demonstrated that the maxima and minima of a transmission spectrum can be used to calculate the refractive index and film thickness with good accuracy when the optical conditions are satisfied [2]. This is particularly useful when profilometry is unavailable or when an independent optical check of thickness is needed.

Transparent oxide semiconductors illustrate why optical and electrical measurements must be interpreted together. Kamiya and Hosono reviewed transparent amorphous oxide semiconductors and highlighted their comparatively high electron mobility despite structural disorder, making them attractive for thin-film transistors and related electronics [4]. Calnan and Tiwari discussed high-mobility transparent conducting oxides for thin-film solar cells, where the desired combination is high transmission and low resistivity [5]. Mallick and Basak later reviewed co-doped ZnO films and showed that dopant combinations, defect chemistry, and microstructure can shift carrier concentration, mobility, resistivity, and optical transmission over wide ranges [11].

Thickness is also a major processing variable. Efker et al. investigated sputtered ZnO layers of different thicknesses and found that thickness influenced optical, structural, and electrical response [9]. Such studies support a methodology in which thickness is treated as an independent variable rather than as a simple fabrication detail.

CdS has been studied extensively because of its wide direct band gap and its usefulness as a window or electron-transport material. Yilmaz et al. showed that Ga and K co-doping can alter transparency, band gap, resistivity, and carrier density in spray-pyrolyzed CdS films [7]. Mahmoud et al. directly examined thickness-dependent optical and electrical behavior in CdS and reported an optical gap around the expected CdS range while also showing that film thickness changes structural and transport characteristics [8]. Ouafi et al. demonstrated that chemical-bath deposition parameters can be adjusted to control CdS thickness while maintaining high visible transmission, emphasizing the influence of processing conditions on optical quality [10].

For CdTe, the absorption edge and structural state are highly relevant because the material functions as an absorber in thin-film photovoltaic devices. Nassar, Yükselci, and Bozkurt investigated CdTe films with different

thicknesses using optical absorption, X-ray diffraction, and Raman spectroscopy; their results showed thickness-dependent changes in the absorption edge, disorder-related parameters, and structural behavior [6]. Together, the ZnO, CdS, and CdTe literature shows that a useful methodology must connect processing, thickness, structure, optical response, and electrical transport in a single analytical sequence.

Methodology

1. Research design and sample plan

A comparative experimental design is proposed using three model thin-film semiconductors: ZnO, CdS, and CdTe. For each material, at least three nominal thickness levels should be prepared (for example, approximately 100, 250, and 500 nm), with a minimum of three replicate specimens at each level. The principal independent variable is film thickness; secondary controlled variables include substrate type, deposition temperature, annealing condition, and measurement temperature. The main dependent variables are average visible transmittance, absorption coefficient, optical band gap, sheet resistance, and bulk resistivity. Supporting variables include crystal structure, crystallite size, and surface morphology.

2. Substrate preparation and film deposition

Step 1 - Substrate cleaning: Use microscope glass for optical measurements and, when needed, conductive or silicon substrates for device-oriented electrical checks. Clean substrates sequentially in detergent/deionized water, acetone, and isopropyl alcohol or ethanol using ultrasonic agitation. Rinse with deionized water and dry with clean air or nitrogen. Consistent cleaning is essential because organic residue and particles can change nucleation, roughness, and contact resistance.

Step 2 - Deposition: ZnO may be deposited by RF magnetron sputtering because this method provides reproducible and uniform oxide films, consistent with thickness-controlled ZnO studies [9]. CdS may be prepared by chemical-bath deposition or spray pyrolysis; the bath route is especially useful for low-temperature growth and thickness control [10], while doped CdS can be studied by spray pyrolysis [7]. CdTe may be deposited by physical or thermal evaporation, as commonly used in thickness-dependent optical studies [6]. The deposition rate, pressure, substrate temperature, bath chemistry, and

deposition time must be recorded for every sample.

Step 3 - Thickness and annealing control: Verify film thickness by stylus profilometry, ellipsometry, cross-sectional microscopy, or optical-envelope analysis when interference fringes are present. Where post-deposition annealing is used, hold all samples at a fixed temperature and duration except when annealing itself is the experimental variable. The final analysis should report both nominal and measured thickness.

3. Optical characterization

Step 4 - UV-Visible measurement: Measure transmittance $T(\lambda)$ and, if available, reflectance $R(\lambda)$ over approximately 300-1100 nm at room temperature. Record a clean substrate as the reference. Average visible transmittance can be computed over a stated wavelength range, for example 400-800 nm. When reflectance is not available and scattering is small, the absorption coefficient can be approximated from transmittance and thickness; for more accurate work, use both T and R and apply the appropriate thin-film optical model.

Step 5 - Band-gap calculation: Convert wavelength to photon energy using $h\nu = 1240/\lambda$, where $h\nu$ is in eV and λ is in nm. For a direct allowed transition, plot $(\alpha h\nu)^2$ versus $h\nu$ and fit the most linear absorption-edge region. Extrapolation of this line to $(\alpha h\nu)^2 = 0$ gives the optical band gap E_g , following the Tauc approach [1]. The fitted energy interval and coefficient of determination should be reported to reduce subjectivity.

Step 6 - Refractive index and optical thickness: If the transmission spectrum contains clear interference maxima and minima, apply the Swanepoel envelope method to estimate refractive index and film thickness [2]. This result can be compared with profilometry as a consistency check. If the spectrum lacks well-defined fringes, do not force the model; report only parameters supported by the available data.

4. Electrical characterization

Step 7 - Four-point probe measurement: Measure voltage and current using a linear four-point probe at several positions on each film. For a sufficiently large uniform film, sheet resistance may be calculated using $R_s = (\pi/\ln 2)(V/I)$, with a geometry correction factor applied when sample dimensions or probe spacing require it, as described in four-point-probe analysis [3]. Compute resistivity from $\rho = R_s \times d$, where d is measured film thickness. Repeat measurements

in at least five positions and report mean $\pm$ standard deviation to capture lateral non-uniformity.

Step 8 - Optional current-voltage and temperature measurements: When device behavior is relevant, deposit defined metal contacts and record current-voltage curves to distinguish ohmic from barrier-dominated behavior. Temperature-dependent conductivity can be added if activation energy or defect-controlled transport is a research objective. These extensions should not replace the basic sheet-resistance measurement because they probe different transport questions.

5. Structural controls and data analysis

Step 9 - Structural/morphological checks: Acquire X-ray diffraction patterns to identify phase and preferred orientation, and use SEM or AFM to evaluate grain structure and roughness. Structural data should be interpreted as explanatory variables rather than as substitutes for optical or electrical measurements. Thickness-related structural changes have been reported for both ZnO and CdTe films [6,9].

Step 10 - Statistical analysis: For each material and thickness level, calculate mean, standard deviation, and coefficient of variation for transmittance, E_g , R_s , and ρ . Test thickness effects by one-way ANOVA when assumptions are met; otherwise use a non-parametric alternative. Correlation analysis can be used to examine whether increased thickness is associated with lower transmittance, shifted band gap, or altered resistivity. The practical target is to identify a processing window that balances optical transmission and electrical conduction for the intended device function.

6. Quality assurance and uncertainty control

Calibration and repeatability should be treated as part of the methodology rather than as optional

checks. The UV-Visible spectrophotometer should be baseline-corrected with the same substrate used for deposition, while wavelength and photometric accuracy should be verified according to the instrument procedure. Thickness measurements should be repeated at several locations to detect gradients across the substrate. For electrical measurements, probe spacing, applied current, contact quality, and sample geometry should remain constant; the current should be low enough to avoid self-heating. Geometry correction factors should be applied where the assumptions of the ideal four-point expression are not met [3].

Uncertainty should be propagated when derived quantities depend on more than one measured variable. For example, resistivity depends directly on both sheet resistance and thickness, so a small thickness error can produce a comparable proportional error in resistivity. Likewise, band-gap extraction depends on the calculated absorption coefficient and the chosen linear fitting interval. Repeating the Tauc fit over a narrowly varied energy window provides a useful sensitivity check. When Swanepoel analysis is used, only well-resolved interference extrema should be included because uncertain maxima or minima can strongly affect the derived refractive index and thickness [2].

7. Reproducibility and reporting

Each sample should receive a unique code linking material, deposition run, thickness target, substrate, and annealing condition. Raw spectra, probe readings, thickness files, and analysis spreadsheets should be retained. Final reporting should state instrument models, scan range, spectral step, deposition settings, number of replicates, data-exclusion rules, and equations used for derived parameters. This reporting structure allows later researchers to separate genuine material differences from differences caused by equipment, fitting choices, or processing history.

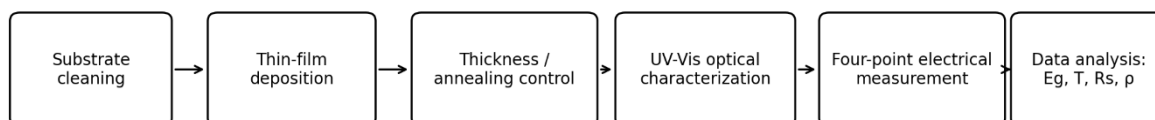


Figure 1. Stepwise workflow for deposition, optical characterization, electrical measurement, and property extraction.

Results

Because this is a methodology paper and no raw laboratory dataset was supplied, the values below are literature-aligned validation targets rather than claimed original measurements. They

indicate the approximate order and direction of results that a correctly executed experiment should be able to reproduce. Actual values must be replaced by the measured data from the selected deposition system.

Table 1. Literature-aligned validation targets for representative semiconductor thin films. *Resistivity varies widely with stoichiometry, doping, defects, contacts, and deposition conditions; ranges are screening guides, not universal constants.

Material	Typical role	Visible T (%)	Eg (eV)	ρ ($\Omega\cdot\text{cm}$)	Expected interpretation
ZnO	Wide-gap oxide / transparent layer	80-90	3.20-3.35	10^{-2} - 10^0	Higher thickness can reduce apparent Eg and transmission; transport is strongly defect/doping dependent [9,11].
CdS	Window / electron-transport layer	70-95	2.40-2.45	10^4 - 10^{6*}	Optical gap near 2.42 eV is common; thickness and doping modify transparency and resistivity [7,8,10].
CdTe	Visible-light absorber	10-40	1.45-1.60	10^4 - 10^{8*}	Strong visible absorption; thickness changes absorption edge, disorder, and structure [6].

A successful experiment should reveal a material-specific balance between absorption and conduction. ZnO is expected to maintain comparatively high visible transmission while its resistivity is strongly affected by defect chemistry and doping. CdS should show a direct optical gap near the mid-2 eV range and can remain highly transparent when sufficiently thin, although undoped or poorly crystallized films may have high resistivity. CdTe should show much stronger visible absorption and a lower optical gap, which is appropriate for an absorber rather than a transparent window layer. These contrasting behaviors provide a useful internal check that the optical analysis is responding to material physics rather than to a data-processing artifact.

Within a given material, thickness trends should be evaluated using measured rather than nominal thickness. In many thin-film systems, increasing thickness reduces average transmission because the optical path length increases. Apparent band-gap shifts may also occur through changes in grain size, disorder, strain, carrier concentration, and fitting range. Electrical resistivity can either decrease as films become continuous and grains grow or increase when additional thickness introduces defects, secondary phases, or altered stoichiometry. Therefore, the interpretation should combine optical, electrical, and structural evidence instead of assuming that one thickness trend applies universally.

Conclusion and Discussion

This methodology provides a concise, reproducible framework for investigating the optical and electrical properties of

semiconductor thin films. Its central principle is that film performance must be evaluated through linked measurements: deposition and thickness control define the physical specimen; UV-Visible spectroscopy provides transmission and absorption behavior; the Tauc method estimates optical band gap; the Swanepoel approach can supply refractive-index and thickness information when interference fringes are present; and four-point probing quantifies sheet resistance and resistivity. Structural measurements then help explain why optical and electrical parameters change with thickness or processing. The literature up to 2018 shows that no single value of transmittance, band gap, or resistivity can characterize all semiconductor thin films. ZnO-based transparent conductors illustrate the need to balance transparency and conductivity [4,5,11]. CdS studies show that thickness, deposition route, and doping can modify both optical transmission and electrical transport [7,8,10]. CdTe studies demonstrate that thickness and microstructure can significantly alter absorption-edge behavior [6]. Consequently, the most meaningful result of the proposed experiment is not a single “best” film but a processing-property map that identifies the thickness and deposition conditions suitable for a particular optoelectronic function. For final experimental reporting, the illustrative ranges in Table 1 should be replaced with original measured values, including replicate statistics and uncertainty. Spectral fitting regions, probe geometry, film-thickness method, contact configuration, deposition parameters, and annealing conditions should all be reported explicitly. This level of methodological transparency makes the study reproducible and

allows comparisons with established thin-film literature without overstating conclusions.

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