ZIBELINE INTERNATIONAL™
PUBLISHING

ISSN: 2521-5051 (Print)
ISSN: 2521-506X (Online)
CODEN: ASMCCQ

Acta Scientifica Malaysia (ASM)

DOI: http://doi.org/10.26480/asm.02.2025.64.70

RESEARCH ARTICLE

SYNTHESIS AND OPTICAL–STRUCTURAL CHARACTERIZATION OF ZNS THIN FILMS DEPOSITED VIA SPRAY PYROLYSIS

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ARTICLE DETAILS

Article History:

Received 10 June 2025
Revised 15 July 2025
Accepted 19 July 2025
Available online 28 August 2025

ABSTRACT

Zinc sulphide (ZnS) thin films are promising materials for optoelectronic and photovoltaic devices due to their wide band gap and high transparency. Their properties, however, are significantly influenced by deposition and annealing conditions. This study aims to synthesize and characterize ZnS thin films deposited at varying substrate temperatures using the spray pyrolysis method, and to examine the influence of temperature on their structural and optical properties. ZnS thin films were deposited on pre-cleaned glass substrates at substrate temperatures of 300 °C and 350 °C using a precursor solution of zinc acetate and thiourea. The films were subsequently annealed at 400 °C. X-ray diffraction (XRD) was used to analyze the structural properties, while UV-Vis spectroscopy was employed to study the optical behavior. XRD analysis revealed that all films exhibited a polycrystalline cubic structure with a preferential (111) orientation. The grain size increased from 20.74 nm to 28.70 nm with rising temperature. Optical measurements showed high transmittance (60–75%) in the visible and near-infrared regions. Band gap energies were found to decrease from 3.35 eV to 2.8 eV as substrate temperature increased. These results demonstrate that substrate temperature significantly affects the microstructure and optical response of ZnS films. In conclusion, the high transparency and tunable band gap make these ZnS films suitable candidates for solar cell windows and optoelectronic components, offering a cost-effective approach via spray pyrolysis.

KEYWORDS

Optical Properties, Spray Pyrolysis, Substrate Temperature, X-ray Diffraction (XRD), ZnS Thin Films

1. INTRODUCTION

The discovery and engineering of new materials have become fundamental drivers of innovation in modern electronic industries. Over the last few decades, the rapid progress in solid-state physics and materials science has led to the development of novel materials with tailored structural, optical, and electronic properties. These advancements are especially critical in microelectronics, optoelectronics, photovoltaics, sensors, and energy storage systems. Semiconductors, which exhibit electrical conductivity between that of metals and insulators, are central to this technological evolution.

Semiconductor materials are broadly classified based on their band gap characteristics and electrical behavior. They have become indispensable in the fabrication of transistors, diodes, light-emitting diodes (LEDs), and photovoltaic devices. Their ability to emit, absorb, and modulate electromagnetic radiation makes them valuable in applications ranging from display technologies to solar energy conversion. Among these, silicon—an indirect band gap semiconductor—has been extensively studied and employed as the base material for most electronic devices (Jacobo, 2002). Despite its advantages, silicon suffers from several drawbacks, particularly in space applications where prolonged exposure to radiation can induce degradation (the Staebler–Wronski effect). Furthermore, its inefficiency in high-speed optical systems has prompted the search for alternative materials that can overcome these limitations (Andriesh et al., 2002).

As a result, researchers have turned to other material systems such as chalcogenides, chalcopyrites, and metal oxides—particularly those doped with transition and rare earth elements—to fulfill the growing need for high-performance semiconductors. These materials exhibit remarkable optical and electronic behaviors and have found applications in a wide range of technologies, including spintronics, photonics, nonlinear optics, and photovoltaic solar cells.

Of particular interest are the binary and ternary chalcogenide semiconductors, which are gaining traction due to their exceptional physicochemical properties and cost-effective synthesis routes. Among these, zinc sulphide (ZnS), a II-VI group binary semiconductor, stands out as a versatile material with a wide band gap (~3.5 eV), high transparency in the visible range, and excellent thermal and chemical stability. These properties make ZnS an attractive candidate for diverse applications, such as window layers in heterojunction solar cells, UV-light-emitting diodes (LEDs), thin-film electroluminescent devices, and phosphors for display technologies (Chiad et al., 2011).

The fabrication of ZnS thin films can be accomplished through a variety of deposition techniques, including chemical vapor deposition (CVD) (Hollingsworth et al., 2003), sulfurization of metal precursors, electrodeposition, co-evaporation, and spray pyrolysis (Muffer et al., 2001; Kuranouchi and Nakazawa, 2008; Scheer et al., 2001; Zouaghi et al., 2001). Each of these techniques has its advantages and limitations in terms of cost, scalability, equipment complexity, and control over film properties. Among them, chemical spray pyrolysis (CSP) has emerged as a promising method due to its simplicity, cost-effectiveness, and capability to produce uniform, adherent, and compositionally tunable films over large substrate

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Cite The Article: Adebayo Samuel, Babatola Babatude.Keji, Adeolu Ajide, Abiona Mujidat Ayobami, Olushola Ebenezer Oluwatobi (2025). Synthesis and Optical–Structural Characterization of ZNS Thin Films Deposited Via Spray Pyrolysis. *Acta Scientifica Malaysia, 9(2): 64-70.*

areas.

CSP offers several advantages: it operates at relatively low substrate temperatures, enables precise control over film thickness and composition, and allows for variation of key parameters such as precursor concentration, substrate temperature, and spray rate. Moreover, it is highly compatible with solution-based precursors, making it environmentally benign and scalable for industrial applications. CSP has been successfully employed in the synthesis of various oxide and chalcogenide thin films including ZnO, In_2O_3, $CuInS_2$, MgO, and ZnS-MgSe (Bouguila et al., 2015).

2. LITERATURE REVIEW

Recent studies emphasize the role of deposition parameters—particularly substrate temperature—in determining the crystallinity, grain size, optical transmittance, and band gap of ZnS thin films. For example, explored the influence of nanoparticle morphology on optical properties, showing that ZnS nanoparticles demonstrate a more uniform distribution compared to other II-VI materials such as CdS (Di Luccio et al., 2006). Their work also underscores the importance of post-deposition annealing and advanced characterization tools such as X-ray diffraction (XRD) and UV-Vis spectroscopy in evaluating film quality.

Manzano et al. (2011) investigated alternative deposition methods such as electrodeposition for ZnO, which provide valuable insight into the economics and temperature sensitivity of thin-film synthesis—findings relevant to ZnS systems. Similarly, examined ultrasonic spray pyrolysis for indium-doped ZnO thin films, showing that water content and substrate temperature significantly affect structural orientation and conductivity (Biswal et al., 2012). These studies reinforce the general principle that meticulous control over synthesis conditions yields films with enhanced optical and electrical performance.

The optical properties of ZnS thin films are particularly important for solar cell applications. As demonstrated that synthesis conditions affect the transparency and refractive index of ZnS films, which in turn influence light absorption and carrier mobility (Jain and Arun, 2013). Sopan Gaikwad et al. (2014) studied the effect of precursor concentration in ZnO films and concluded that changes in molarity influence the crystallite size and optical constants, such as the extinction coefficient and optical density.

As explored synthesis approaches for porous ZnO thin films, confirming that surface morphology and porosity can be tuned by modifying spray pyrolysis parameters (Laurenti and Cauda, 2018). Their work supports the growing consensus that spray pyrolysis is a versatile technique not only for dense films but also for nanostructured morphologies.

As reviewed the potential of spray pyrolysis in synthesizing high-k dielectric materials and luminescent coatings (Falcony et al., 2018). They discussed early work on ZnS nanoparticles and emphasized the reproducibility and adaptability of the technique across various classes of functional materials. This adaptability is crucial in meeting the increasing demands for high-efficiency optoelectronic components.

More recently, focused on ZnO thin films for photovoltaic applications, underlining the influence of dopants and annealing on film conductivity and transparency (Bouaichi, 2019). Similarly, introduced an energy-efficient chemical bath deposition technique for Zn-based films, offering a comparative benchmark for evaluating CSP (Temel et al., 2019).

Research on ZnO-ZnS heterostructures demonstrated how sulfurization processes influence band alignment and carrier transport properties (Das, 2019). As presented results on spray-deposited ZnO thin films for field-effect transistors, affirming the critical role of precursor chemistry and surface treatment in achieving desired conductivity and optical transparency (Cho et al., 2019).

As explored the fabrication of amorphous ZnOx films at cryogenic temperatures, revealing their potential for flexible electronics and transparent conducting oxides (Zubkins et al., 2022). As evaluated the effect of capping agents on ZnS nanoparticle synthesis, showing how surface chemistry can be manipulated to achieve controlled crystallinity and band gap tuning (Mandal et al., 2023).

Collectively, these studies underscore the growing importance of ZnS and related materials in cutting-edge applications. Despite the diversity of synthesis routes, CSP remains a frontrunner due to its adaptability and reproducibility. The focus of the present study is to synthesize high-quality ZnS thin films via the chemical spray pyrolysis method at varying substrate temperatures and to systematically analyze their structural and optical properties. The goal is to understand how substrate temperature influences film morphology, crystallinity, grain size, transmittance, reflectance, absorption, and optical band gap—parameters that are vital for tailoring ZnS films for solar cells, UV sensors, gas sensors, smart windows, and transparent electronic devices.

3. METHODOLOGY

3.1 Materials and Equipment

The precursor chemicals used for the synthesis of ZnS thin films were zinc acetate dihydrate ($Zn(CH_3COO)_2{\cdot}2H_2O$) as the zinc source, and thiourea (NH_2CSNH_2) as the sulfur source. Both reagents were of analytical grade and used without further purification. Two solvent systems were utilized: distilled water alone and a binary solvent system comprising distilled water and ethanol in a 1:1 volume ratio. To maintain and adjust the pH of the precursor solution, acetic acid and ammonia solution were added as buffering agents. The role of these additives was to stabilize the precursor complex and promote uniform film formation during deposition.

Glass microscope slides with dimensions 76.0 mm × 25.0 mm × 1.5 mm served as substrates for film deposition. Prior to use, the substrates were thoroughly cleaned using a sequence of detergent wash, ultrasonic agitation in distilled water, and final rinsing with chromic acid solution to remove organic and inorganic contaminants. Substrates were then air-dried and stored in a contamination-free environment.

The deposition was carried out using a Chemical Spray Pyrolysis (CSP) system, which included a PID temperature controller, solid-state relay (SSR), hot plate, K-type thermocouple, substrate holder, compressed air source, and a fine-nozzle spray gun. Additional laboratory apparatus included precision digital weighing balances, 100 mL measuring cylinders, 250 mL conical flasks, 50 mL beakers, magnetic stirrers, washing bowls, and protective hand gloves. The entire setup was designed to ensure uniform precursor spraying and consistent substrate heating for optimal thin film growth.

3.2 Preparation of Precursor Solution

The precursor solution used for the deposition of ZnS thin films was prepared using analytical-grade reagents: zinc acetate dihydrate [$Zn(CH_3COO)_2{\cdot}2H_2O$] as the zinc source, and thiourea [NH_2CSNH_2] as the sulfur source. Both compounds were used to prepare 0.2 M equimolar solutions. Accurately weighed quantities of 4.39 g of zinc acetate dihydrate and 1.522 g of thiourea were each dissolved in 100 mL of distilled water to obtain their respective 0.2 M solutions.

The two solutions were mixed in a 1:1 molar ratio in a clean 250 mL conical flask and stirred continuously using a magnetic stirrer to ensure uniform mixing. The resulting mixture was then subjected to pH adjustment using a drop of dilute acetic acid. The pH was carefully monitored and adjusted to fall within the range of 5 to 6, which has been reported to be ideal for stable ZnS precursor complexation. The mixture was further stirred for 30 minutes to achieve complete homogenization, eliminate local concentration gradients, and ensure total dissolution of solutes. This step is critical to prevent the formation of precipitates during spray deposition and to ensure uniform film growth.

The values of molar mass, mass, molarity, and solution volume for each chemical component used in the preparation of the precursor solution are provided in Table 1.

Table 1: Composition of the precursor solution

S/N	Chemical	Molar Mass (g/mol)	Mass (g)	Molarity (mol/L)	Volume (mL)
1	Zinc Acetate Dihydrate	219.50	4.39	0.2	100
2	Thiourea	76.12	1.522	0.2	100
3	Ammonia Solution	17.03	1.67	0.25	1 drop
4	Distilled Water	18.00	206.00	55.56	100

3.3 Substrate Cleaning Procedure

Prior to deposition, the glass substrates (dimensions: 76.0 mm × 25.0 mm × 1.50 mm) were rigorously cleaned to ensure the removal of all organic, inorganic, and ionic contaminants, which could otherwise interfere with thin film adhesion and uniformity. Three microscope glass slides were first scrubbed thoroughly with laboratory-grade detergent and rinsed multiple times using double-distilled water to remove surface grease and particulates.

Subsequently, the substrates were placed in a beaker containing methanol and ultrasonicated for 30 minutes to eliminate deeply embedded surface residues. After methanol cleaning, the substrates were immersed in 0.1 M hydrochloric acid (HCl) and left to soak for 12 hours to dissolve ionic contaminants and residual metallic impurities. Following acid treatment, the substrates were rinsed again in acetone for 10 minutes to neutralize any remaining acidic residues and promote surface activation. The cleaned substrates were then removed and allowed to air-dry in a dust-free environment in preparation for thin film deposition.

This multi-stage cleaning procedure is essential for achieving uniform nucleation and strong adhesion of the ZnS thin film onto the substrate surface.

$$Volume, v = \frac{mass, m \times 100}{Density \times Purity} \quad (1)$$

$$mole, n = \frac{mass, m}{molarmass, M_m} \quad (2)$$

$$Molarity, C = \frac{mole, n}{Volume, V} \quad (3)$$

$$Mass, m = (Molarity, C) \times (Molarmass, M_m) \times (Volume, V) \quad (4)$$

3.3.1 Chemical Synthesis

A 0.2 M zinc acetate solution was prepared by accurately weighing 4.39 g of zinc acetate dihydrate using a digital weighing balance and dissolving it in 100 mL of distilled water. Separately, 1.522 g of thiourea was also dissolved in 100 mL of distilled water to obtain a 0.2 M solution. The two solutions were then combined and thoroughly mixed. To facilitate complex formation and stabilize the solution, a drop of ammonia solution was added. The resulting mixture was stirred continuously for 30 minutes using a magnetic stirrer to ensure complete homogenization and to enhance molecular interaction between the reactants. This step is essential for achieving a uniform precursor solution, which promotes consistent film deposition during the spray pyrolysis process. The preparation setup, including the digital weighing balance, ultrasonic cleaner, and magnetic stirrer, is shown in Figure 1.

Figure 1: Digital Weighing Balance, Ultrasonic Cleaner, and Magnetic Stirrer.

3.3.2 Thin Film Deposition Using Ultrasonic Chemical Spray Pyrolysis

The Ultrasonic Chemical Spray Pyrolysis (CSP) technique was employed in this study for the deposition of ZnS thin films due to its notable advantage of allowing simultaneous variation and control of multiple deposition parameters. This versatility facilitates the optimization of film growth conditions and the synthesis of uniform, high-quality thin films. The deposition parameters used are as follows:

- Substrate Temperatures: 300 °C and 350 °C
- Outlet Gas Pressure: 30 psi
- Deposition Time: 3 minutes
- Spray Rate: 10 mL/min
- Nozzle-to-Substrate Distance: 30.0 cm

Figure 2: Spray pyrolysis setup including PID temperature controller, hot plate, and spray gun.

The deposition was performed using a locally constructed spray pyrolysis system, illustrated in Figure 2, which consists of a spray gun, a K-type thermocouple, a hot plate with a PID (Proportional–Integral–Derivative) temperature controller, and a power supply ranging between 1500–3000 W. The substrate heating was achieved through a thermally conductive hot plate connected to the PID controller, ensuring uniform temperature distribution across the substrate surface. The cleaned glass substrates were placed directly on this heated plate.

NO_2 gas was introduced via an air compressor to maintain a constant outlet pressure of 30 psi, which facilitated the formation and delivery of fine aerosol droplets. The precursor solution was atomized and sprayed at a rate of 10 mL/min from a height of 30 cm onto the heated substrate. Upon contact, the droplets spread, evaporate, and undergo pyrolytic decomposition, forming a dense, adherent ZnS thin film. The process was repeated at both substrate temperatures to evaluate thermal effects on film morphology and crystallinity.

Post-deposition, all samples were annealed in air at 400 °C for 1 hour to investigate the impact of thermal treatment on structural and optical properties, as aligned with the study's objectives.

3.4 Annealing Process

An annealing process was conducted at a temperature of 400 °C to enhance the quality of the deposited ZnS thin films by reducing impurity contamination and promoting improved structural properties. Annealing plays a critical role in the recrystallization and phase transformation of thin film materials, particularly in the transition from an amorphous to a polycrystalline phase. This transformation is essential for improving the crystallinity, grain orientation, and overall uniformity of the ZnS films, which in turn enhances their optical and electronic behavior.

Numerous studies have reported that annealing significantly influences the optical band gap of semiconductor materials. As crystallinity improves with increasing temperature, the band gap tends to decrease due to the reduction in defect states and enhanced long-range order in the material structure. For ZnS thin films, this phenomenon has been confirmed in the work, who demonstrated that post-deposition thermal treatment leads to a measurable decrease in the band gap, indicating improved film quality (Nelly-Ann Molland, 2014).

4. RESULTS AND DISCUSSION

4.1 Structural Properties

The crystalline structure of the ZnS thin films was analyzed using an EMPYREAN X-ray diffractometer equipped with CuKα radiation (λ = 1.540598 Å). The X-ray diffraction (XRD) technique was employed to determine the phase composition, crystallinity, and preferred orientation of the deposited films. XRD measurements were conducted for films deposited at two substrate temperatures—300 °C and 350 °C—both subjected to post-deposition annealing at 400 °C.

The diffractograms, presented in Figure 3, show a distinct diffraction peak located near 28° (2θ), which is associated with the (111) crystallographic plane of cubic ZnS. This peak reflects the development of polycrystalline structure with a strong preferential orientation. The presence and intensity of this peak serve as indicators of the crystallinity of the films.

As shown in Figure 3a, the film deposited at 300 °C exhibited relatively weak diffraction intensity, indicating the early stages of crystallization. In contrast, Figure 3b, corresponding to the film deposited at 350 °C, displays a sharper and more intense diffraction peak. This enhancement in peak intensity is attributed to improved crystallinity and increased grain growth, driven by the higher thermal energy available during deposition.

The average crystallite sizes of the films were estimated from the diffraction data and were found to be 20.74 nm for the film deposited at 300 °C and 28.70 nm for that at 350 °C. This confirms that higher substrate temperatures promote better atomic arrangement and larger grain formation. These findings are consistent with previously reported results (e.g., Djelloul et al., 2015), which demonstrate the significant impact of substrate temperature on the microstructural quality of ZnS thin films.

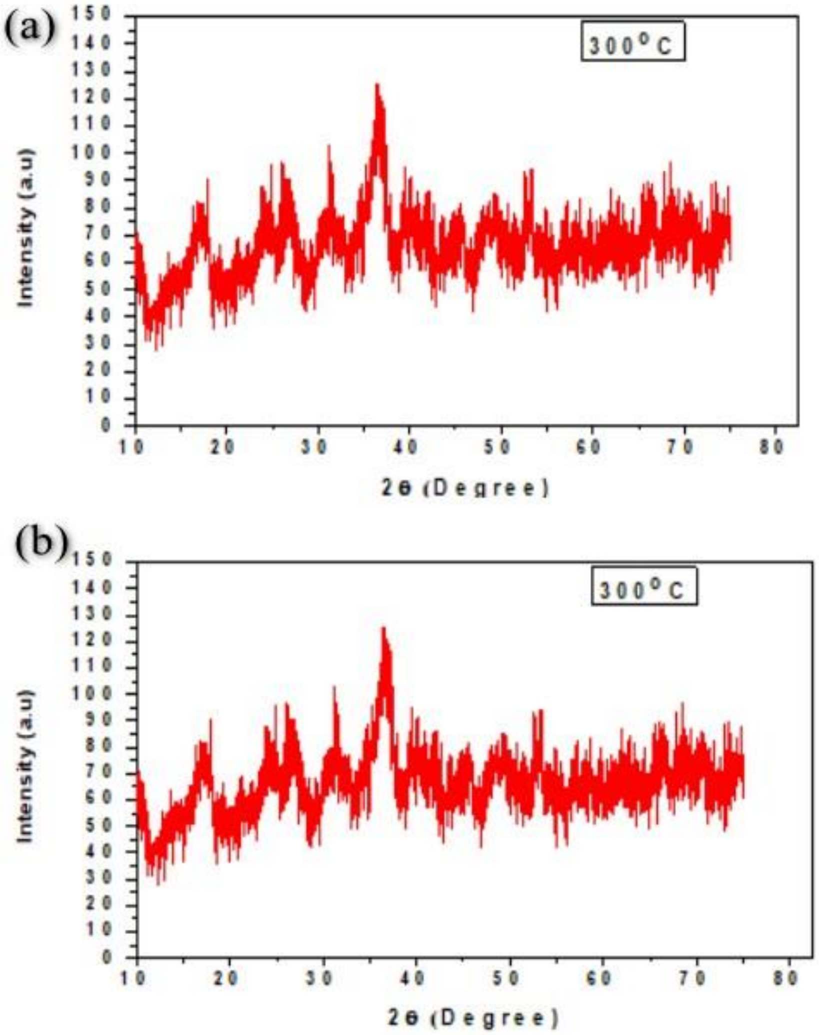

Figure 3: XRD patterns of ZnS thin films deposited at (a) 300 °C and (b) 350 °C, both annealed at 400 °C.

4.2 Optical Properties Measurements

The study of optical properties is essential for understanding the behavior and performance of semiconductor materials in optoelectronic applications. In this research, the optical characteristics of ZnS thin films deposited at substrate temperatures of 300 °C and 350 °C were investigated. Both films were subjected to a post-deposition annealing process at 400 °C to enhance their structural and optical quality.

4.2.1 Transmission (T)

The optical transmittance of the ZnS thin films was measured at room temperature using a UV-Vis spectrophotometer in the wavelength range of 300 nm to 850 nm. The results are presented in Figure 4, which includes transmittance spectra for films deposited at 300 °C (Figure 4a), 350 °C (Figure 4b), and a comparative plot of both temperatures (Figure 4c), all annealed at 400 °C.

As shown in the figure, transmittance increases steadily with increasing wavelength for both samples. This behavior is characteristic of semiconducting thin films, where lower absorption occurs in the visible to near-infrared regions. Notably, the film deposited at the higher substrate temperature of 350 °C exhibited slightly higher transmittance across most of the spectrum compared to the film deposited at 300 °C. This improvement is attributed to enhanced crystallinity and reduced defect states, resulting from elevated substrate temperatures.

The highest transmittance was observed in the visible and near-infrared regions (400–850 nm), which makes ZnS thin films suitable for solar cell window layers, optical coatings, dielectric filters, and reflectors. These results align with the findings, who also reported increased transparency in ZnS films synthesized by spray pyrolysis at elevated temperatures (Bouguila et al., 2015). The high optical transparency confirms the potential of ZnS as a promising material for optoelectronic applications where light transmission is crucial.

Cite The Article: Adebayo Samuel, Babatola Babatude.Keji, Adeolu Ajide, Abiona Mujidat Ayobami, Olushola Ebenezer Oluwatobi (2025). Synthesis and Optical–Structural Characterization of ZNS Thin Films Deposited Via Spray Pyrolysis. *Acta Scientifica Malaysia, 9(2):* 64-70.

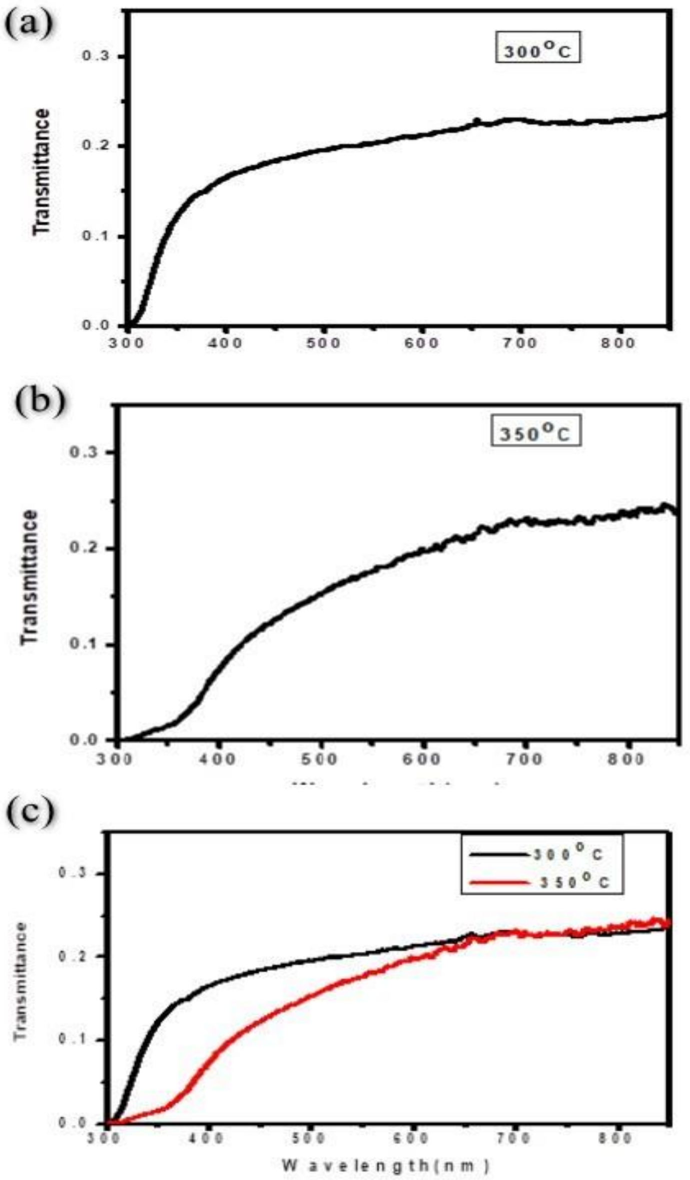

Figure 4: Transmittance spectra of ZnS thin films annealed at 400 °C, deposited at substrate temperatures of (a) 300 °C, (b) 350 °C, and (c) both 300 °C and 350 °C.

4.2.2 Reflectance (R)

Reflectance, defined as the ratio of reflected beam intensity to incident radiation, can be determined using spectral absorbance and transmittance data (Jasib and Yousif, 2015). The reflectance behavior of ZnS thin films as a function of wavelength is illustrated in Figure 5. The data reveal that the reflectance (R) remains nearly constant in the wavelength range of 600–850 nm, indicating minimal variation in optical response in the near-infrared region. However, a sharp decline in reflectance is observed between 490–590 nm, suggesting that photon energies greater than the material's band gap (hν > Eg) are strongly absorbed. This implies that at photon energies below the band gap, ZnS films absorb very little light. Furthermore, the overall reflectance in the visible and near-infrared regions is relatively low, a desirable property for optical and photovoltaic applications. Reflectance tends to increase with higher substrate temperatures, consistent with previous findings (Saeed, 2011).

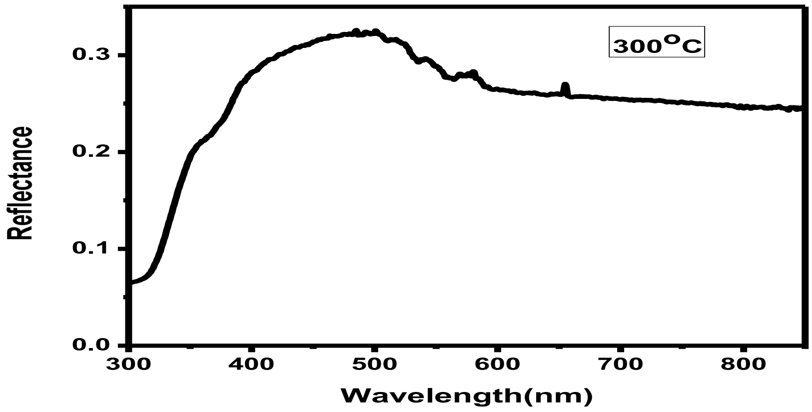

Figure 5: Reflectance of ZnS thin film deposited at 300 °C and annealed at 400 °C.

4.2.3 Absorption (A)

The absorbance spectra of ZnS thin films deposited at different substrate temperatures were analyzed to evaluate their optical absorption behavior. Figure 6 shows the absorbance curves for films prepared at 300 °C and 350 °C, both annealed at 400 °C. The results reveal that ZnS thin films exhibit strong absorption in the short wavelength (UV) region, which gradually decreases as the wavelength increases. This behavior is typical of semiconducting materials with a wide band gap. The high absorbance in the UV region indicates that the ZnS films are capable of efficiently absorbing high-energy photons. As the photon energy decreases with increasing wavelength, the absorption drops significantly. Notably, absorption begins to rise sharply once the photon energy approaches the energy band gap of the material, signifying electronic transitions from the valence band to the conduction band. This observation aligns with the findings, confirming that band gap transitions govern the optical absorption behavior of ZnS thin films (Saeed, 2011).

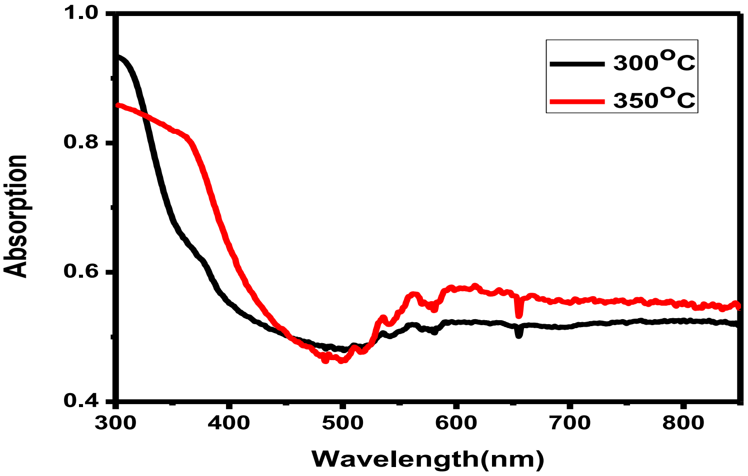

Figure 6: Absorbance spectra of ZnS thin films deposited at 300 °C and 350 °C, annealed at 400 °C.

4.3 Optical Energy Gap

The optical energy band gap of ZnS thin films was determined based on the direct allowed electronic transition between the valence band and the conduction band. For such transitions, the absorption coefficient (α) follows the Tauc relation for direct band gap semiconductors, where the exponent r is ½. The band gap values were obtained by plotting $(\alpha hv)^2$against the photon energy $(hv)^2$ and extrapolating the linear portion of the curve to the energy axis, as shown in Figure 7.

The extracted energy band gaps for ZnS thin films deposited at substrate temperatures of 300 °C and 350 °C (both annealed at 400 °C) were found to be 3.35 eV and 2.80 eV, respectively. The observed decrease in band gap with increasing deposition temperature is attributed to improved crystallinity and reduced quantum confinement effects at higher substrate temperatures. This trend suggests that substrate temperature significantly influences the optical properties of ZnS thin films.

Notably, the film with the higher band gap of 3.35 eV (at 300 °C) exhibits strong potential for optoelectronic applications such as multilayer dielectric filters and window layers in solar cells. A wider band gap minimizes absorption losses in the visible region, thereby enhancing light transmission and improving the short-circuit current of solar cells. These results are in good agreement with findings, who also reported temperature-dependent band gap variations in ZnS thin films (Djelloul et al., 2015; Saeed, 2011).

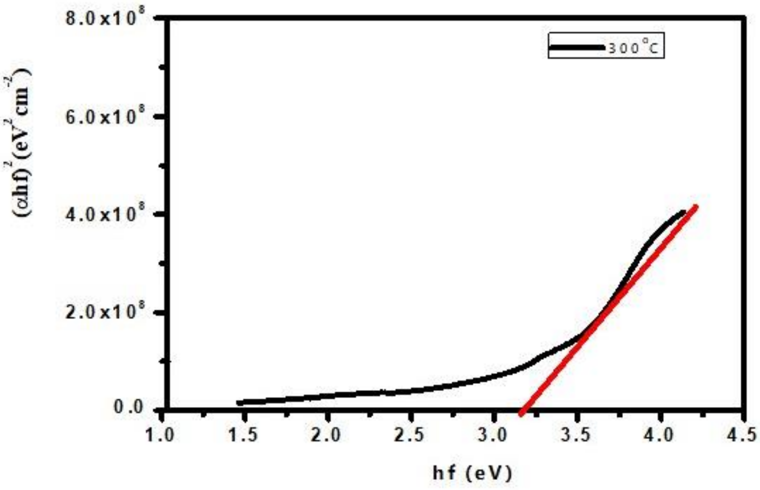

Figure 7: Optical energy band gap of ZnS thin films deposited at 300 °C and 350 °C, annealed at 400 °C.

X-ray diffraction (XRD) analysis revealed that the ZnS thin films possess a polycrystalline cubic structure with a strong (111) preferential orientation. The calculated grain sizes ranged from 20.74 nm to 28.70 nm, increasing with higher substrate temperatures, indicating improved crystallinity at elevated thermal conditions. Optical measurements showed that the films exhibited high transparency within the visible and near-infrared regions, with transmittance values ranging from 60% to 75%. The refractive index of the films was found to be in the range of 3.04 to 3.07, consistent with values expected for high-quality ZnS layers.

Furthermore, optical band gap energies were determined to be 3.35 eV for films deposited at 300 °C and 2.80 eV for those at 350 °C, demonstrating a clear dependence of the band gap on substrate temperature. This variation suggests that substrate temperature significantly influences the electronic structure of the material. Due to their wide band gap and high transmittance, the ZnS thin films are well-suited for solar cell window layers and optoelectronic device applications, particularly where minimal absorption and high transparency are desired.

5. CONCLUSION

In this study, high-quality ZnS thin films were successfully synthesized using the chemical spray pyrolysis (CSP) method at two substrate temperatures: 300 °C and 350 °C. The objective was to investigate how deposition temperature influences the structural and optical properties of ZnS films. All films were subjected to post-deposition annealing at 400 °C to enhance their crystallinity and remove residual impurities. The X-ray diffraction (XRD) analysis confirmed that the ZnS thin films crystallize in a polycrystalline cubic structure with a pronounced (111) preferential orientation. The crystallinity improved significantly with increasing substrate temperature, as reflected in the sharper diffraction peaks and larger grain sizes. Specifically, the grain size increased from 20.74 nm at 300 °C to 28.70 nm at 350 °C, indicating enhanced atomic ordering and crystal growth due to increased thermal energy. Optical characterization using UV-Vis spectroscopy revealed that the films possess excellent transparency in the visible to near-infrared range, with transmittance values ranging between 60% and 75%. This high transparency makes the films ideal candidates for applications as window layers in solar cells, optical coatings, and dielectric filters. Additionally, the refractive index of the films was found to lie between 2.8 and 3.0, further supporting their applicability in optoelectronic and photonic devices. The optical band gap values were calculated using Tauc plots and showed a clear dependence on substrate temperature. Films deposited at 300 °C exhibited a band gap of 3.35 eV, while those deposited at 350 °C showed a reduced band gap of 2.80 eV. This trend can be attributed to improved crystallinity and reduced structural defects at higher temperatures, leading to a narrowing of the energy gap. This work demonstrates that substrate temperature plays a crucial role in tuning the structural and optical properties of ZnS thin films synthesized via spray pyrolysis. The films produced at 350 °C with post-annealing exhibit superior crystallinity, higher transparency, and an optimized optical band gap, making them well-suited for integration in solar energy harvesting systems, UV photodetectors, and optoelectronic devices.

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Cite The Article: Adebayo Samuel, Babatola Babatude.Keji, Adeolu Ajide, Abiona Mujidat Ayobami, Olushola Ebenezer Oluwatobi (2025). Synthesis and Optical–Structural Characterization of ZNS Thin Films Deposited Via Spray Pyrolysis. *Acta Scientifica Malaysia, 9(2):* 64-70.