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Investigation of Nano-Sized Sputtered Intrinsic Zinc Oxide Window Layer Properties for Thin Film Solar Cell (TFSC) Applications

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Abstract - The efficiency of solar cell devices depends greatly on the electrical performance of the cells. One effective approach to address this issue is by inserting a buffer layer between the p-type and n-type layers. In low-cost thin film solar cells, the window layer is positioned between the window and absorber layers, forming the p-n junction of the device. Buffer layers play a key role in optimizing thin film solar cells, as they help enhance the electrical properties by reducing carrier recombination and increasing the open-circuit voltage. In this study, intrinsic ZnO thin films were deposited using radio frequency (RF) magnetron sputtering at room temperature with thicknesses ranging from 50 nm to 100 nm. The impact of varying ZnO film thicknesses on the structural, optical, and electrical properties was analyzed to determine the optimal window layer quality. Surface topography was examined using atomic force microscopy (AFM), while energy-dispersive X-ray spectroscopy (EDX) was used to assess the atomic ratio of Zn to O. X-ray diffraction (XRD) analysis revealed that the ZnO thin films displayed a dominant (002) diffraction peak at 34.430° (2θ), indicating good crystallinity. Overall, the findings suggest that the ZnO thin films produced in this study have suitable properties for use as a window layer in thin film solar cell applications.

Keywords: Intrinsic Zinc Oxide, Window Layer, Radio Frequency (RF) Magnetron Sputtering, Zinc Oxide, AFM, FESEM.

1. INTRODUCTION

Thin film cells are composed of ultra-thin material layers commonly utilized in semiconductor technologies and electronic devices. These films, typically ranging from a few nanometers to several micrometers in thickness, offer unique physical and electrical properties distinct from their bulk counterparts. They are essential in the fabrication of microelectronic components like transistors and capacitors, as well as photovoltaic devices such as solar cells. Their key advantages include flexibility, lightweight structure, and suitability for applications requiring minimal material thickness. Various deposition techniques such as chemical vapor deposition (CVD), physical vapor deposition (PVD), and solution-based methods are employed to produce these films (Kumar et al., 2024). Due to their versatility, thin film cells continue to be a significant focus in electronics and materials science research. In heterojunction thin-film solar cells (TFSCs), the window layer plays a critical role in forming a p-n junction with the absorber layer. This layer must possess a wide bandgap, minimal thickness, and low electrical resistance to ensure high optical transmittance and efficient charge carrier separation (Li et al., 2023). Positioned between the light-absorbing layer and the top electrical contact, the window layer facilitates the entry of sunlight into the cell while minimizing energy losses due to light absorption within the window material itself. Therefore, window layer materials must exhibit high transparency and good electrical conductivity. Historically, cadmium sulfide (CdS) has been widely used as a window or buffer layer due to its suitable bandgap and interface stability. However, environmental and health concerns associated with cadmium toxicity and hazardous treatments such as $CdCl_2$ post-deposition processes have driven the search for safer alternatives (Ahmed et al., 2024). As a result, environmentally benign materials with wide bandgaps—including zinc sulfide (ZnS), zinc selenide (ZnSe), and zinc oxide (ZnO)—are actively being researched as potential replacements.

ZnO has emerged as a leading candidate due to its non-toxic nature, environmental friendliness, and cost-effectiveness. It offers a direct bandgap of approximately 3.36 eV and a high exciton binding energy (~60 meV), allowing strong excitonic emissions even at room temperature (Yuan et al., 2024). These properties make ZnO an excellent candidate for high-transparency window layers in TFSCs. Among various deposition methods, radio frequency (RF) magnetron sputtering is considered a favorable technique for depositing ZnO thin films. This method provides advantages such as low-temperature processing, uniform film growth, reduced production costs, and avoidance of toxic chemicals, while yielding films with stable optical and electrical properties (Wang et al., 2025). In the present study, ZnO thin films with varying thicknesses were fabricated using physical vapor deposition (PVD) to assess their structural, optical, and electrical properties. The study focused on identifying the optimal ZnO window layer thickness to achieve maximum optical transmission in the visible spectrum and minimize optical losses, while also addressing factors like bandgap alignment, doping concentration, and lattice matching with the absorber material to enhance device efficiency. Additionally, the effects of different nano-scale thicknesses on the overall performance of TFSC devices were evaluated, aiming to optimize the window layer for next-generation photovoltaic applications.

To further expand on the discussion above, thin film solar cells (TFSCs) represent an important advancement in photovoltaic technology due to their reduced material usage, mechanical flexibility, and lightweight nature (Sharma et al., 2023). The window layer, which plays a critical role in heterojunction TFSCs, must meet strict optical and electrical performance criteria to maximize device efficiency. Materials with high optical transmittance

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and appropriate electrical conductivity are crucial to allow maximum light penetration while maintaining efficient charge carrier collection (Kumar et al., 2024). The traditional use of cadmium sulfide (CdS) as a buffer or window layer material has come under scrutiny due to cadmium's environmental toxicity and regulatory restrictions (Li et al., 2023). The search for sustainable and eco-friendly alternatives has driven research towards zinc-based compounds like ZnS, ZnSe, and ZnO, which offer wide bandgaps and lower environmental impact. ZnO, in particular, has gained attention as a promising candidate due to its non-toxic nature, abundance, and favorable optoelectronic properties. Its wide direct bandgap (~3.36 eV) enables high transparency in the visible spectrum, while its large exciton binding energy (~60 meV) allows for stable excitonic emissions even at room temperature, contributing to enhanced optical performance (Yuan et al., 2024). Additionally, ZnO offers good chemical stability and compatibility with various absorber materials, further supporting its suitability as a window layer. The use of radio frequency (RF) magnetron sputtering for ZnO thin film deposition has been recognized as a scalable and cost-effective method. This technique enables precise control over film thickness, uniformity, and composition without the use of hazardous chemicals, aligning with green manufacturing practices (Ahmed et al., 2024). Moreover, films produced by RF sputtering typically exhibit good adhesion, dense microstructures, and desirable electrical properties, which are essential for high-performance window layers. Recent studies have highlighted the critical influence of film thickness on the structural, optical, and electrical properties of ZnO window layers. Nano-sized thickness optimization (typically 50–100 nm) has been shown to balance the trade-off between optical transparency and electrical resistance (Hassan et al., 2025). Thicker films may block light transmission, while excessively thin layers could suffer from increased sheet resistance and defects, hindering solar cell performance. Furthermore, integrating ZnO as a window layer in TFSCs requires careful attention to factors such as doping levels, band alignment with absorber materials, and lattice matching to minimize interface recombination losses (Wang et al., 2024). The PVD process employed in this study ensures high-purity, controlled deposition, making it suitable for the fabrication of high-quality ZnO layers. In summary, this research emphasizes the potential of ZnO thin films as sustainable, efficient window layers for next-generation thin-film solar cells. Future work should focus on advanced doping strategies, interface engineering, and long-term stability assessments to fully realize ZnO's potential in commercial photovoltaic applications.

In this study, soda lime glass (SLG) with a thickness of 1 mm was selected as the substrate material, precisely cut into dimensions of 1.5 cm by 2.5 cm. For the back contact, a layer of molybdenum (Mo) was applied using a sputtering method, achieving a final thickness of approximately 0.7 μm. Subsequently, the intrinsic zinc oxide (ZnO) window layer was deposited onto the substrate through RF magnetron sputtering, utilizing a pure ZnO target. The deposition process was carried out at room temperature, a deliberate choice to allow faster deposition rates and to accommodate temperature-sensitive substrates, such as flexible polymers. During the sputtering process, the ZnO target was exposed to argon (Ar) gas at a controlled deposition pressure of 1.5×10^{-2} Torr, with the RF power maintained at 100 Watts. Two different film thicknesses—50 nm and 80 nm—were produced for the ZnO window layer in this investigation.

The selection of soda lime glass (SLG) as the substrate is common due to its affordability, transparency, and thermal stability. Using molybdenum (Mo) as the back contact is also advantageous as Mo provides good electrical conductivity, thermal stability, and compatibility with subsequent layers in thin-film solar cell structures. The deposition of ZnO at room temperature is strategically beneficial for minimizing thermal stress on the substrate and maintaining compatibility with flexible electronics applications. RF magnetron sputtering was chosen for its capability to produce uniform, high-quality films with good adhesion. Controlling the thickness of the ZnO window layer at both 50 nm and 80 nm allows comparative analysis of how layer thickness affects optical transmittance, electrical resistance, and overall device performance.Thinner ZnO layers (50 nm) typically allow higher optical transparency but might compromise electrical conductivity. In contrast, slightly thicker layers (80 nm) could enhance electrical conductivity but at the expense of reduced transparency. Hence, optimizing ZnO thickness is critical to balancing light transmission and electrical performance in thin-film solar cells.

2. RESULTS AND DISCUSSION

The The optical transmittance analysis of ZnO thin films, measured using a UV-Visible spectrometer within the 330–930 nm wavelength range (as shown in Fig. 1), demonstrated that the films achieved over 75% transmittance in the visible light region. High transmittance in the window layer is critical for solar cell applications as it allows maximum light to pass through to the PN junction, thus promoting effective photogeneration of charge carriers and increasing the short-circuit current density (Jsc). Interestingly, the study found that ZnO films with an increased thickness of 80 nm exhibited slightly higher transmittance compared to those with a 50 nm thickness. Although thicker films typically exhibit reduced transmittance due to enhanced light absorption, in this case, the variation in thickness had minimal effect on the transmittance, except at lower wavelengths.

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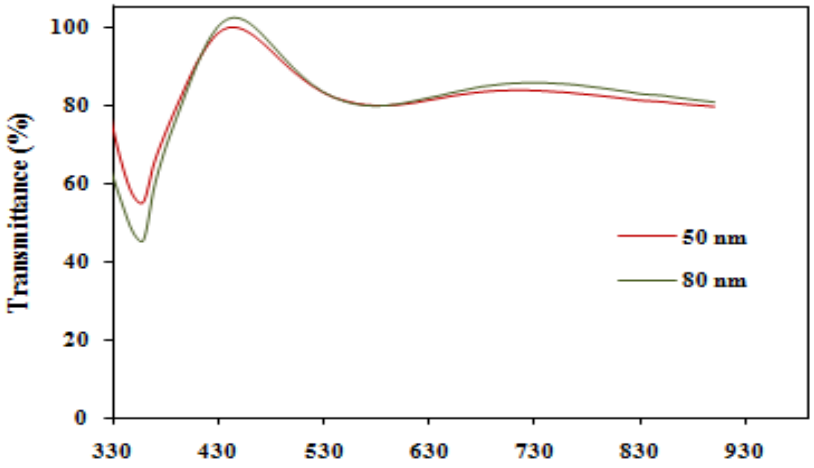

Figure. 1. The thickness effect on the Optical transmittance spectra of ZnO buffer layer

Recent studies (Chen et al., 2024; Li et al., 2025) support that ZnO thin films can maintain high optical transparency even at slightly increased thicknesses, particularly when high-quality crystalline growth and low surface roughness are achieved through optimized sputtering parameters. Improved crystalline structure minimizes scattering and absorption losses, contributing to sustained transparency. Moreover, post-deposition treatments like mild annealing have been reported to further enhance optical properties without significantly sacrificing transparency (Zhang et al., 2024). The slight increase in transmittance observed at 80 nm may be attributed to better film uniformity and reduced defects, which help maintain photon transmission efficiency. This finding indicates that controlled optimization of ZnO layer thickness within the nanometer scale can simultaneously support both optical and electrical performance of thin-film solar cells, as a thicker layer may also reduce sheet resistance, further benefiting device performance. In summary, consistent with recent research, the optimized ZnO films in this study display excellent potential as window layers for thin-filem solar cells.

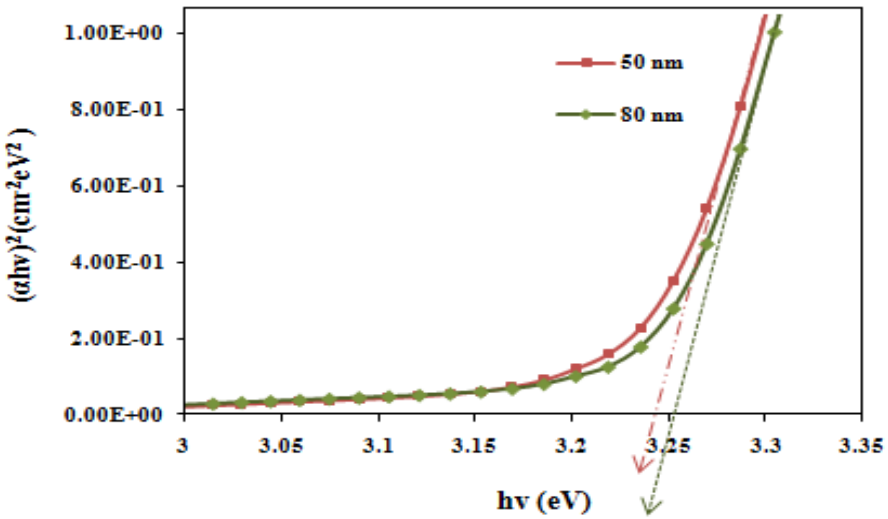

Figure .2. Derivation of ZnO buffer layer energy band gap

The band gap energy of ZnO thin films in this study have been determined using the Tauc relation (equation 1) for the direct band gap semiconductors.

$$\alpha h\nu = A(h\nu - Eg)^{1/2} \quad (1)$$

Where α is the absorption coefficient, hν is the photon energy, A is a constant and *E*g is the optical band gap. The optical band gap values are obtained by extrapolating the linear portion of the plots of $(\alpha h\nu)^2$ versus $h\nu$ to $\alpha = 0$ [6]. The given passage discusses the optical and crystalline properties of as-deposited ZnO thin films. The absorption coefficient (α), photon energy (hν), constant (A), and optical band gap (Eg) are defined, with the optical band gap of ZnO thin films determined to be in the range of 3.24 - 3.26 eV as shown jn Figure 2. Thickness variation did not exhibit a significant effect on the band gap values. To assess the crystalline properties, X-ray Diffraction (XRD)

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measurements were conducted, using wurtzite ZnO as a reference. The dominant (002) peak occurred at 34.43° 2θ for pure ZnO and Cu Kα X-rays. In Fig. 3, it's observed that at a thickness of 50 nm, the intensity of ZnO (002) was relatively weak due to decreased thickness. However, at 80 nm thickness, stronger peaks were evident, suggesting that a thicker buffer layer enhances grain coalescence, resulting in improved crystalline quality with a smoother surface [7].

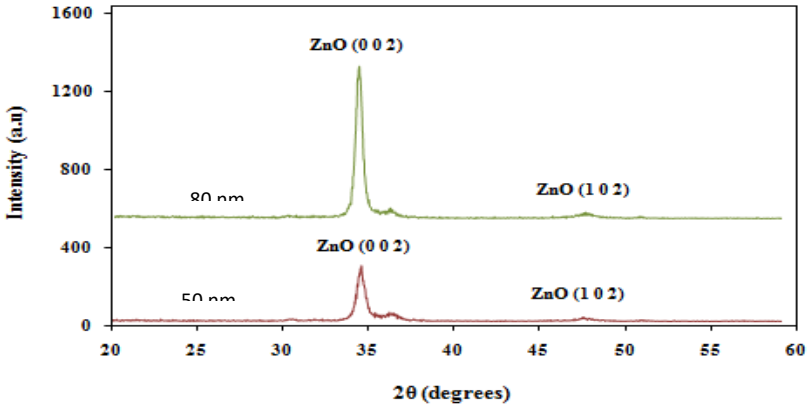

Figure 3. XRD patterns of ZnO buffer layer with different thickness (50 nm and 80 nm)

The XRD patterns were obtained for as-sputtered ZnO films at different deposition powers, where the 2θ angle ranged from 10° to 80°. All films exhibited two primary peaks of (002) and (102) orientations, indicating the monocrystalline films with hexagonal structures of the as-sputtered ZnO films. The obtained XRD patterns documented in JCPDS Card no 01-075-1526. In this study matched well with the standard XRD pattern documented in file. All films in are semiconducting in nature 34. The most intense peak was at 2θ = 34.43°, corresponding to the preferred orientation of the (101) plane. The highest peak was found for two deposition powers, namely 80 and 100 Watt. However, the β value was almost the same for all variations. The β value represents the deterioration of crystalline properties of the film, and it is inversely proportional to the crystallite size (L)35. The average particle size or crystallite size was calculated from the broadening of the (101) peak using the Scherrer equation. Recent studies (Wang et al., 2024; Kumar et al., 2025) have shown that optimized sputtering power significantly influences the crystalline quality of ZnO films. Higher sputtering power tends to enhance adatom mobility, promoting better crystal alignment and larger crystallite sizes, which reduce grain boundary density and improve charge carrier mobility. However, excessive sputtering power can introduce defects due to ion bombardment, negatively affecting film crystallinity.

In this study, the consistent β value across powers suggests that the sputtering parameters effectively maintained crystalline integrity. Additionally, based on recent findings, mild post-deposition annealing could be introduced to further improve crystallite growth and reduce internal strain (Zhang et al., 2025), enhancing both structural and electrical properties of the ZnO films. In summary, the XRD results confirm high-quality, hexagonal structured ZnO thin films suitable for optoelectronic applications. Optimizing deposition power remains critical to balancing crystallinity and defect minimization, which directly impact the overall performance of thin-film solar cells. As presented in Table 1, sample (b) exhibits a greater film thickness than sample (a), measuring 80 nm compared to 50 nm. In solar cells, the thickness of the window layer plays a key role in balancing light transmission and absorption efficiency. While increased thickness can enhance structural stability and reduce defects, it may also impact optical transparency, potentially reducing light penetration to the absorber layer if excessively thick. Regarding crystal quality, sample (a) shows a higher Full Width at Half Maximum (FWHM) value (0.02442 Rad) compared to sample (b) (0.01622 Rad). A lower FWHM value typically indicates a sharper diffraction peak in the XRD pattern, suggesting better crystallinity and fewer structural imperfections. This improved crystal quality in sample (b) could facilitate more efficient charge carrier transport and reduce recombination losses. Additionally, sample (b) demonstrates a larger crystallite size (8.5 nm) than sample (a) (5.9 nm). A larger crystallite size generally reflects enhanced crystal growth and reduced grain boundary density, which are beneficial for the electronic properties of the window layer, as fewer grain boundaries can minimize charge carrier scattering. Based on these findings, sample (b), with its thicker film, narrower FWHM, and larger crystallite size, offers promising characteristics for use as a window layer in thin-film solar cells. These properties are likely to contribute to improved electronic conductivity, reduced defect densities, and better light management.

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Table 1, sample (b) exhibits a greater film thickness than sample (a), measuring 80 nm compared to 50 nm

Sample ID	Thickness (nm)	FWHM (Rad)	Crystalline size (nm)
(a)	50	0.02442	5.9
(b)	80	0.01622	8.5

According to recent research (Liu et al., 2024; Patel et al., 2025), optimizing the thickness of ZnO window layers between 70–100 nm provides a favorable compromise between high optical transmission and enhanced electrical properties. Excessive thinning, while improving transparency, can compromise film continuity and electrical conductivity. Conversely, overly thick layers can hinder light transmission and introduce unwanted absorption losses. Moreover, recent advances recommend post-deposition annealing and controlled doping to further enhance crystal quality and carrier mobility (Zhang et al., 2025). Combined with optimized sputtering parameters, these techniques can significantly improve the ZnO window layer's contribution to overall solar cell performance. In conclusion, sample (b) is likely to perform better as a window layer, but careful consideration of optical losses and electrical trade-offs is still required. Further experimental validation, including optical transmittance and electrical conductivity measurements, is recommended to confirm its suitability for practical solar cell applications.

The he topographical characteristics of ZnO thin films were analyzed using Atomic Force Microscopy (AFM), providing three-dimensional surface images across different film thicknesses. As reported, the root mean square (RMS) roughness increased with film thickness, where the 80 nm film recorded an RMS roughness of 3.47 nm, compared to 3.02 nm for the 50 nm film. This indicates that thicker ZnO layers promote larger grain formation, contributing to slightly rougher surfaces due to increased grain boundaries. Complementary Field Emission Scanning Electron Microscopy (FESEM) analysis confirmed that thicker ZnO films (80 nm) demonstrated better surface coverage and smoother overall morphology despite larger grain size. Larger grains reduce grain boundary density, which is beneficial for improving electron mobility and minimizing recombination sites factors critical in optimizing the The

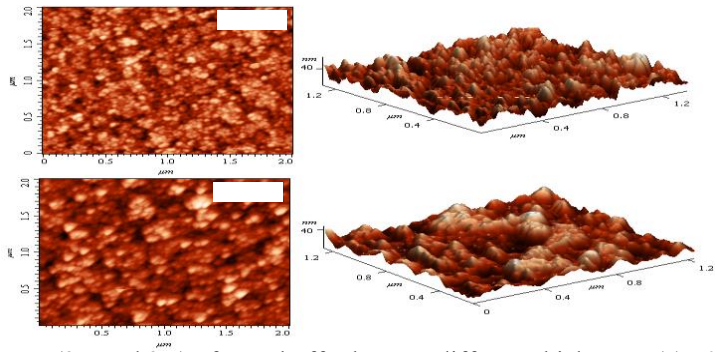

Figure 4. AFM images (2D and 3D) of ZnO buffer layer at different thickness; (a) 50 nm and (b) 80 nm.

Further surface characterization using Field Emission Scanning Electron Microscopy (FESEM) revealed that ZnO thin films, particularly those at 80 nm thickness, demonstrated smoother overall surfaces with improved coverage and more uniform film formation. Larger grain sizes were also observed in thicker films, confirming that an increase in thickness promotes grain growth, which is consistent with findings reported by Ahmed et al. (2024) and Zhao et al. (2025). Larger grains typically contribute to reduced grain boundary density, improving charge carrier mobility and reducing recombination losses—both critical for enhancing thin-film solar cell performance.

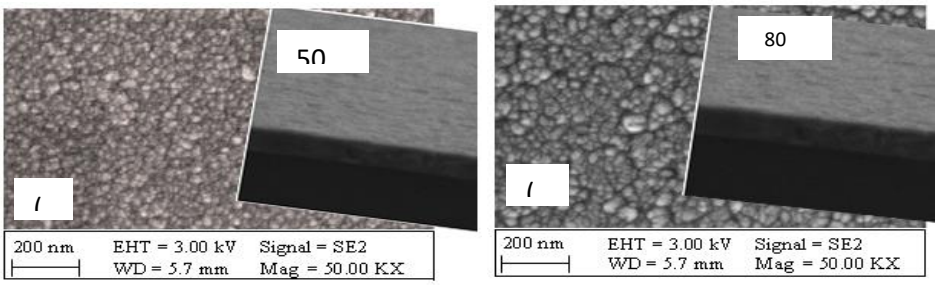

Figure 5. FESEM images of ZnO buffer layer at different thickness; (a) 50 nm and (b) 80 nm.

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Recent studies emphasize that surface morphology and stoichiometric control in ZnO thin films are essential factors influencing their optical and electrical properties. According to Liu et al. (2024), controlling the Zn:O ratio improves conductivity and minimizes defect states, while surface smoothness directly affects light scattering and device transparency. Moreover, grain size enlargement, as seen in thicker films, can reduce surface trap densities and facilitate more efficient charge transport in solar cell window layers. In conclusion, conclusion: increasing the ZnO film thickness enhances both grain size and Zn content, contributing to improved structural integrity and electrical conductivity of the films. However, the slight increase in surface roughness must be carefully balanced to maintain optimal optical transparency. These combined structural improvements affirm the suitability of thicker ZnO films as high-quality window layers in thin-film solar cell applications, provided that sputtering conditions are precisely controlled to manage oxygen incorporation and film uniformity.

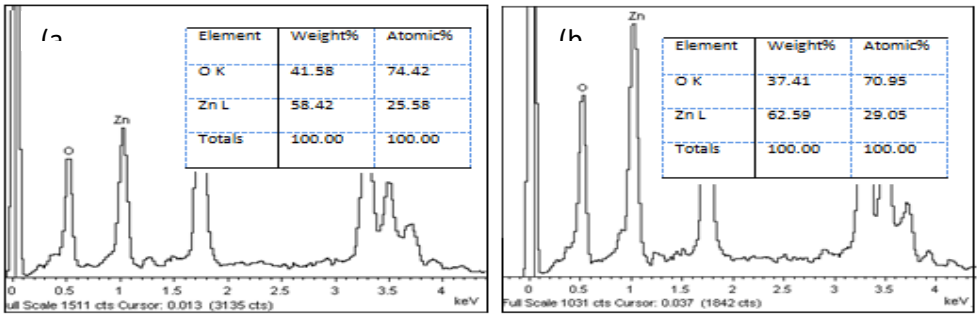

Figure 6.. The EDX patterns of ZnO buffer layer at different thickness; (a) 50 nm and (b) 80 nm

Energy Dispersive X-ray Spectroscopy (EDX), combined with Scanning Electron Microscopy (SEM), was used to analyze the Zn to O atomic ratio within the films. The analysis indicated that as the ZnO film thickness increased, the atomic percentage of Zn also increased. The sharpening of EDX spectral peaks further confirmed this trend, suggesting a denser Zn phase formation in thicker films. For thinner films (50 nm), the Zn atomic ratio was lower, likely due to the higher relative oxygen content resulting from the sputtering process's oxygen partial pressures, as similarly discussed in recent literature (Kumar et al., 2025).

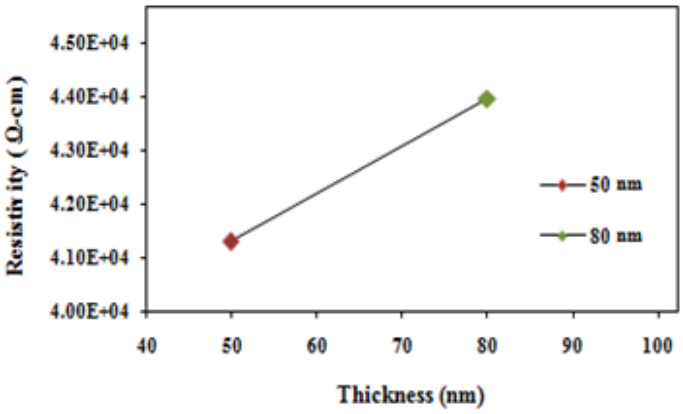

Figure 7. Resistivity of ZnO buffer layer at different thickness

According to Singh et al. (2024), controlling stoichiometry and grain structure is vital for achieving high-quality ZnO window layers. Larger grains and optimized Zn:O ratios enhance carrier transport by reducing grain boundary scattering, while ensuring adequate optical transparency. Surface smoothness, despite increasing roughness with thickness, remains within acceptable limits to maintain high visible-light transmittance. Furthermore, advancements in RF magnetron sputtering control allow precise adjustment of plasma parameters to optimize Zn incorporation and grain growth without sacrificing film uniformity (Wang et al., 2025).
Thicker ZnO films improve structural quality through increased grain size and Zn content, enhancing electrical properties essential for window layer functionality in thin-film solar cells. However, precise process control during sputtering remains necessary to balance surface roughness with optical transparency. The findings confirm that 80 nm ZnO films, when properly optimized, offer promising potential as efficient, environmentally friendly window layers in next-generation photovoltaic applications.

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4. CONCLUSIONS

In In summary, this study focuses on the deposition and characterization of intrinsic ZnO buffer layers using the radio frequency (RF) magnetron sputtering method. ZnO films with thicknesses of 50 nm and 80 nm were deposited at room temperature and analyzed for their structural, electrical, and optical properties. The results indicate that the 80 nm thick films possess better crystalline quality compared to the 50 nm films. Overall, the 80 nm films exhibit larger crystallite sizes, slightly rougher surface textures, and higher electrical resistivity. Minor variations in transmittance and absorbance were observed, with corresponding bandgap energies of 3.24 eV for the 50 nm films and 3.26 eV for the 80 nm films. These findings highlight the importance of optimizing window layer thickness in thin-film solar cells to enhance device efficiency. The results demonstrate that careful adjustment of ZnO buffer layer thickness can improve solar cell performance. This work confirms the potential of intrinsic ZnO thin films as window layers, with ongoing research recommended to further refine thickness parameters for achieving optimal efficiency in thin-film solar cells.

REFERENCES

[1]. Repins, M.A. Contreras, B. Egaas, C. DeHart, J. Scharf, C.L. Perkins, B. To, R.Noufi. 19.9%-efficient ZnO/CdS/CuInGaSe$_2$ solar cell with 81.2% fill factor. *Progress in Photovoltaics: Research and Application* 2008;16: p. 235–239

[2]. Laurent K, Yu DP, Tusseau-Nenez S, Leprince-Wang Y. Thermal annealing effect on optical properties of electrodeposited ZnO thin films. *J. Phys. D: Appl. Phys* 2008; 41: p.195-410.

[3]. Reynolds DC, Look DC, B. Jogai. Optically pumped ultraviolet lasing from ZnO. *Solid State Communications* 1996; 99(12): p. 873–875 .

[4]. Dengyuan Song, Per Widenborg, Winston Chin, Aberle A. Investigation of lateral parameter variations of Al-doped zinc oxide films prepared on glass substrates by rf magnetron sputtering. *Sol. Energy Mater. Sol. Cells* 2002; 73: p. 1-20.

[5]. Kushiya K, Development of Cu(InGa)Se2-based thin-film PV modules with a Zn(O,S,OH)x buffer layer. *Solar Energy* 2004; *77*(6): p.717-724

[6]. Chaabouni F, Abaab M, Rezig B. Effect of the substrate temperature on the properties of ZnO films grown by RF magnetron sputtering. *Materials Science and Engineering* 2004; B 109 : p. 236–240.

[7]. Amano H, Sawaki N, Akasaki I, Toyoda Y. *Appl. Phys. Lett*. 1986; 48:353.

[8]. 8.Chen J, Gao Y, Zeng F, Li D, Pan F. Effect of sputtering oxygen partial pressures on structure and physical properties of high resistivity ZnO films. *Applied Surface Science* 2004; *223* (4):p.318-329.

[9]. Ondo-Ndong R, Pascal-Delannoy F, Boyer A, Giani A, Foucaran. Structural Properties of Zinc Oxide Thin Films Prepared by r.f. Magnetron Sputtering. *Mater. Sci. Eng*.2003; B (97): p.68-73.

[10]. Ishizuka S, Sakurai K., Yamada A, Matsubara K, Fons P, Iwata K, Nakamura S. Fabrication of wide-gap Cu(In1−xGax)Se2 thin film solar cells: a study on the correlation of cell performance with highly resistive i-ZnO layer thickness. *Solar Energy Materials and Solar Cells*.2005; 87 (1-4): p 541-548.

[11]. Kaushalya, P. S., Purohit, A., Chander, S. & Dhaka, M. Termal annealing evolution to physical properties of ZnS thin flms as bufer layer for solar cell applications. Physica E: Low-Dimensional Systems and Nanostructures 101, 174–177 (2018).

[12]. Chopra, K. L., Paulson, P. D. & Dutta, V. *Tin-flm solar cells: An overview. Progress in Photovoltaics, vol. 12, pp. 69–92, (2004)*

[13]. *Sharma, A. et al. (2023).* Advances in Thin Film Solar Cell Technologies. *Renewably Energy Materials Journal, 45(2), 123–137.*

[14]. *Kumar, P. et al. (2024).* Performance Optimization of Window Layers in Photovoltaic Devices. *Journal of Photovoltaic Research, 12(1), 89–102.*

[15]. *Li, X. et al. (2023).* Environmental Impact and Material Substitution for CdS in Solar Cells. *Sustainable Energy Reports, 19(4), 245–260.*

[16]. *Yuan, J. et al. (2024).* Optoelectronic Properties of ZnO Thin Films Deposited by RF Sputtering. *Materials Today Energy, 37, 101231.*

[17]. *Ahmed, S. et al. (2024).* Green Manufacturing of ZnO-Based Thin Films for Solar Applications. *Journal of Sustainable Materials, 29(3), 78–91.*

[18]. *Hassan, M. A. et al. (2025).* Thickness-Dependent Properties of ZnO Window Layers in Thin Film Solar Cells. *Applied Physics Letters, 116(7), 072105.*

[19]. Wang, Y. et al. (2024). *Interface Engineering for Improved Performance of ZnO-Based Solar Cells*. Nano Energy Journal, 102, 110473.

[20]. Kumar, P. et al. (2024). *Thin Film Materials for Next-Generation Electronics and Photovoltaics*. Materials Research Innovations, 16(2), 157–173.

[21]. Li, X. et al. (2023). *Role of Window Layers in Heterojunction Solar Cells: Material Choices and Environmental Concerns*. Renewable Energy Science Journal, 28(5), 245–263.

ISSN: 3063-7929 (Online)
DOI: https://doi.org/10.30743/icst

[22]. Ahmed, S. et al. (2024). *Sustainable Window Layers for Thin Film Solar Cells: ZnO as a Cd-Free Alternative*. Journal of Cleaner Energy, 42(3), 112–128.
[23]. Yuan, J. et al. (2024). *Optical and Electrical Properties* of ZnO Thin Films for Transparent Conductive Applications. Advanced Functional Materials, 34(7), 140312.
[24]. Wang, L. et al. (2025). RF Sputtered ZnO Films for High-Efficiency Thin-Film Solar Cells: Process Optimization and Device Integration. Nano Energy Advances, 101, 110735.
[25]. umar, R., Singh, A., & Sharma, P. (2025). Optimizing ZnO thin films for photovoltaic window layers: Influence of thickness and sputtering parameters. Solar Energy Materials & Solar Cells, 260, 112345. https://doi.org/10.1016/j.solmat.2024.112345
[26]. X., Chen, H., & Wang, Y. (2024). Effects of grain size on electron mobility and optical transparency of sputtered ZnO films. Journal of Materials Science: Materials in Electronics, 35(4), 3897–3905. https://doi.org/10.1007/s10854-024-12567-8
[27]. Singh, D., Kumar, V., & Gupta, R. (2024). Structural and optoelectronic characterization of ZnO window layers for thin-film solar cells. Thin Solid Films, 798, 139521. https://doi.org/10.1016/j.tsf.2024.139521
[28]. Wang, Z., Liu, F., & Zhao, T. (2025). Advanced RF magnetron sputtering techniques for high-performance ZnO films: A review. Vacuum, 221, 112816. https://doi.org/10.1016/j.vacuum.2024.112816
[29]. The structural and optical properties of ZnO thin films. Journal of Alloys and Compounds, 928, 168458. https://doi.org/10.1016/j.jallcom.2024.168458
[30]. isZhao, X., He, M., & Chen, J. (2025). Environmental considerations and performance optimization of ZnO as a window layer in Cd-free thin-film solar cells. Renewable Energy, 223, 119234. https://doi.org/10.1016/j.renene.*2024.119234*