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Morphological and Electrical Characterization of ZnO Co-Doped with Al and B Via Sol-Gel for Window Layer Applications in Solar Cells

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Abstract

This paper presents the synthesis and characterization of zinc oxide (ZnO) films co-doped with aluminum (Al) and boron (B) via sol-gel method for use as a window layer in photovoltaic devices. The morphology of the particles, degree of crystallinity, and size distribution of the ZnO particles are critical parameters to window layer performance, and were examined by high-resolution transmission electron microscopy (HRTEM) and selected area electron diffraction (SAED). The electrical properties of the films were assessed using the Hall Effect method. As a result, the film's resistivity of 3.18 x $10^{-4,}$, carrier concentration of 6.2 x 10^{20} and the mobility of 31.7 $cm^2/V•s$ demonstrated that the charge transport properties of the ZnO:Al:B films were comparable to high-quality indium tin oxide (ITO). Based on HRTEM analysis, the particle size of undoped ZnO is 24.40 nm, but decreases for ZnO:Al, ZnO:B, and ZnO:B:Al to 20.48 nm, 23.83 nm, and 17.30 nm respectively. ZnO:Al:B co-doped thin film can be considered a viable alternative to ITO in photovoltaic solar cell applications, offering comparable electrical performance with the added advantages of lower material cost and greater elemental abundance.

Keywords: ZnO; Doping; Sol-Gel; Aluminum; Boron.

Introduction

The modern world is powered by Energy. It is essential for every nation's development both economically and technologically (Alsagri, 2022). The primary driver of the rise in energy demand in the upcoming years would be attributed to the accelerating rate of growth in population, industry, and per capita energy consumption (W. Wu & Lin, 2022). The world's oil supplies are not sufficient to rely on in the foreseeable future, and conventional energy sources are neither dependable nor sustainable. As a result, the challenge is to find sustainable and renewable energy sources with affordable prices and minimal negative effects on the environment (Hassan & Mohamad, 2012). "The increasing global demand for sustainable and renewable energy sources has intensified research into photovoltaic (PV) technologies as viable alternatives to fossil fuels. Solar energy, being abundant, clean, and environmentally friendly, has become one of the most promising renewable energy sources for addressing global energy challenges and reducing greenhouse gas emissions (Li et al., 2019). Numerous renewable energy sources, such as wind, solar, hydro, and geothermal, where developed as more sustainable options for producing clean and environmentally friendly energy. Furthermore, solar power has drawn a lot of interest among these sources due to its enormous potential to extract solar energy (Holechek et al., 2022). A valuable alternative where other renewable sources might not be practical is solar electricity, which also has the potential to be used outside of the Earth's surface (Neha & Rambeer, 2021).

Utilizing photovoltaic has shown to be a useful method for efficiently converting solar energy into electrical power and solar cells are fundamental element in this process (Pastuszak & Węgierek, 2022). The first generation of solar cells were constructed from Silicon (Si), which was previously the predominant material utilized in the absorber layer of solar cells, especially on an industrial scale. However, more recent research has identified other materials with superior fundamental properties as alternatives to Si, such as Copper Indium Gallium Selenide (CIGSe) and Cadmium Telluride (CdTe)(Regmi et al., 2023). These materials have an adjustable band gap, a greater absorption coefficient and may even be somewhat flexible (Doroody et al., 2022).

In order to minimize energy losses, it is essential to ensure that sunlight penetrates the absorber layer properly and that the generated charges are collected efficiently given the presence of materials other than Si (Regmi et al., 2023). This study is significant in several respects, particularly in the context of advancing materials for photovoltaic applications and contributing to the broader field of renewable energy research. Firstly, the study contributes to the ongoing search for cost-effective and sustainable alternatives to conventional transparent conductive oxides (TCOs) such as indium tin oxide (ITO). Due to the high cost and limited availability of indium, there is a growing need for alternative materials that can deliver comparable or superior performance. By investigating aluminum and boron co-doped ZnO thin films, this research provides valuable insights into the development of

low-cost, abundant, and environmentally friendly materials for solar cell applications (Alsaad et al., 2020). Secondly, the study enhances scientific understanding of the effects of co-doping on the structural and electrical properties of ZnO thin films. While previous research has explored single doping, the combined effects of aluminum and boron remain less extensively studied, particularly in relation to their synergistic influence on crystallinity, transparency, and defect reduction. The findings of this study will therefore contribute to the existing body of knowledge by clarifying how co-doping modifies ZnO properties and improves its performance (Li et al., 2019). Another important contribution of this research lies in its focus on the sol–gel dip coating technique, which is recognized for its simplicity, low cost, and scalability. By demonstrating the feasibility of producing high-quality co-doped ZnO thin films using this method, the study supports the development of economically viable fabrication processes for large-scale production of solar cell components (Mahmood & Naeem, 2017). This is particularly relevant for regions with limited access to advanced deposition technologies.

Furthermore, the study has practical significance in improving the performance of solar cells. The optimization of ZnO thin films as window layer materials can lead to enhanced light transmission, reduced energy losses, and improved charge carrier transport, all of which contribute to higher energy conversion efficiency (Koralli et al., 2022). As global energy demand continues to rise, such improvements are essential for making solar energy a more competitive and widely adopted power source. The research also provides a foundation for future studies by identifying optimal doping concentrations and processing conditions that yield desirable film properties. This can guide further investigations into electrical characterization, device fabrication, and real-world application of co-doped ZnO thin films (Regmi et al., 2023).In addition, the study has academic significance as it serves as a reference material for students and researchers in the fields of physics, materials science, and nanotechnology. It demonstrates the integration of experimental techniques, material synthesis, and characterization methods, thereby contributing to scientific training and capacity building. Finally, from an environmental and societal perspective, the study supports the global transition toward clean and renewable energy technologies. By promoting the use of non-toxic, abundant materials and low-energy fabrication methods, the research aligns with sustainable development goals aimed at reducing environmental impact and ensuring energy security (Alsagri, 2022).

Therefore, this study aims to investigate the structural and electrical properties of aluminum and boron co-doped ZnO thin films prepared using the sol–gel dip coating technique, with a view to assessing their suitability as efficient window layer materials in solar cell applications (Orori, 2023).

PROBLEM STATEMENT

The global transition toward renewable energy sources has positioned photovoltaic technology as a cornerstone of sustainable energy infrastructure. However, the widespread adoption of solar cells continues to face significant challenges related to cost, efficiency, and material

sustainability(W. Wu & Lin, 2022). Transparent conducting oxides (TCOs) serve as critical components in thin-film solar cells, functioning as window layers that must simultaneously maximize light transmission into the active layer while facilitating efficient charge carrier extraction(Chavan et al., 2023). Indium tin oxide (ITO) has historically dominated this application due to its exceptional optoelectronic properties, yet its continued use presents fundamental problems: indium is a scarce element with limited global reserves, its extraction and refining processes carry substantial environmental burdens, and market price volatility creates economic uncertainty for large-scale photovoltaic manufacturing (Castañeda, 2022). ITO also suffers from stability issues in outdoor applications. The material exhibits susceptibility to moisture-induced degradation, commonly referred to as "mildew" formation, which occurs when ITO absorbs water and carbon dioxide from the atmosphere and undergoes chemical reactions that degrade its electrical and optical properties(Gultepe & Atay, 2022). This degradation mechanism presents significant challenges for long-term outdoor photovoltaic applications.(Sarma et al., 2019). Zinc oxide (ZnO) has emerged as a promising alternative material system owing to its natural abundance, non-toxicity, chemical stability, and favorable electronic properties. However, undoped ZnO exhibits high electrical resistivity that renders it unsuitable for transparent electrode applications without intentional doping. While single-element doping with aluminum (Al) or boron (B) has demonstrated improvements in electrical conductivity, these approaches encounter inherent limitations. Aluminum-doped ZnO films often suffer from reduced optical transparency at higher doping concentrations due to increased free carrier absorption and impurity scattering. Boron-doped ZnO films, while offering superior transparency, typically exhibit lower electrical conductivity than their aluminum-doped counterparts (Khantoul et al., 2018). The sol–gel dip coating method offers several advantages, including low cost, ease of processing, and scalability(Singh & Scotognella, 2023). A critical gap in existing research is the limited systematic investigation into the combined effects of Al and B co-doping on ZnO thin films prepared specifically via the sol–gel dip coating technique for different precursor concentrations. While some studies have explored co-doping using other deposition methods, there is insufficient data on how process parameters in sol–gel dip coating influence the interaction between dopants, crystallinity, and optical transmittance (D. Zhao et al., 2022). This research will bridge the gap between the excellent properties of ITO and ZnO by co- doping ZnO film with Al and B by optimizing its precursor concentration. The result will not only produce a TCO with improved structural and electrical properties but safer, easy to produce, but making it more available at cheaper window layer of solar cells.

OBJECTIVES

- To prepare Zinc Oxide (ZnO) thin- film by sol-gel method.
- To prepare Boron doped with Zinc oxide (ZnO:B) thin- film by sol-gel method.
- To prepare Aluminum doped with Zinc oxide (ZnO:Al) thin- film by sol-gel method.
- To prepare Aluminum and Boron Co-Doped Zinc Oxide (ZnO:Al:B thin- film by sol-gel method

- To the determine morphological and electrical properties of ZnO, ZnO:Al, ZnO:B and ZnO:Al:B by characterization with high-resolution transmission electron microscopy (HRTEM) and Hall- Effect measurement

LITERATURE REVIEW

Transparent Conductive Oxide (TCO), often composed of oxide-based materials. Thin-film solar cells use TCO as the uppermost layer because of its better conductivity and high transparency. With their improved conductivity and transparency under visible light, hold significant potential for usage in photovoltaic and electronics applications (Gultepe & Atay, 2022). TCOs have a wide range of important applications. Because of their unique blend of electrical conductivity and optical transparency, they are widely utilized as electrical contacts for solar cells and light-emitting diodes (Chavan et al., 2023). Traditionally, indium tin oxide (ITO) has been widely used as a TCO due to its excellent electrical and optical properties. However, the high cost, scarcity of indium, and environmental concerns associated with ITO have driven the search for alternative materials (Adjimi et al., 2018). Among the various alternatives, zinc oxide (ZnO) has emerged as a strong candidate due to its abundance, non-toxicity, chemical stability, and favorable optoelectronic properties. ZnO is a II–VI semiconductor with a wide direct bandgap (~3.3 eV), making it highly transparent in the visible region while maintaining good electrical characteristics when appropriately doped (Bel-Hadj-Tahar & Mohamed, 2014). Zinc oxide compound is a practical substitute for ITO. One of the key challenges associated with ZnO as a TCO is its relatively low intrinsic electrical conductivity. Pure ZnO is typically an n-type semiconductor due to native defects such as oxygen vacancies and zinc interstitials, but the carrier concentration is often insufficient for high-performance applications. To address this limitation, ZnO is commonly doped with donor elements, particularly group III elements such as aluminum (Al), gallium (Ga), and indium (In), which substitute for Zn sites in the lattice and contribute free electrons to the conduction band (Koralli et al., 2022). Among these dopants, aluminum is particularly attractive due to its low cost, abundance, and effectiveness in enhancing conductivity. Aluminum-doped ZnO ((ZnO: A) has been widely studied and is considered one of the most promising TCO materials for solar cell applications. Similarly, boron doping has been shown to influence the structural and optical properties of ZnO, often leading to improved film uniformity and reduced defect density (Naser et al., 2022). Aluminum acts as a donor impurity, increasing free electron concentration, while boron can improve structural stability and refine grain structure (Shweta & Thapa, 2019). In addition to material composition, the fabrication technique significantly influences the structural, optical, and electrical properties of thin films (Amakali et al., 2020).. Among various deposition methods such as sputtering, chemical vapor deposition (CVD), and pulsed laser deposition, the sol–gel dip coating method stands out due to its simplicity, low cost, ease of composition control, and ability to produce uniform thin films over large area (Orori, 2023). This method is particularly advantageous for large-scale production and research applications (Kondratiev et al., 2013). Despite significant progress,

there remain challenges in optimizing the doping concentration, film uniformity, and annealing conditions to achieve the ideal balance between optical transparency and electrical conductivity. Furthermore, the combined effects of aluminum and boron co-doping on ZnO thin films prepared via sol–gel dip coating are not yet fully understood, particularly in the context of their application as window layers in solar cells (Gultepe & Atay, 2022). In summary, ZnO stands out as a highly promising TCO material due to its excellent optical transparency, tunable electrical properties through doping, chemical stability, and cost-effectiveness. Continued research into doping strategies, particularly co-doping with elements such as aluminum and boron, is essential for optimizing its performance and expanding its application in next-generation photovoltaic devices(Wojtasik et al., 2023).

Preparation of Zinc oxide (ZnO) Solution

Thin- films of ZnO was prepared by sol-gel dip-coating. Zinc acetate dihydrate was first dissolved in a 50mL of 2-methoxyethanol in a dry 50mL beaker to achieve concentration of 0.091M, 0.273M, and 0.455M (corresponding to 1g. 2g, 5g of salt). "The solution was stirred between 400 - 500 rpm at room temperature for 15mins with a magnetic stirrer to ensure uniform distribution of particles (Bouacheria *et al*., 2022). Monoethanolamine was added at a 1:1 molar ratio to Zn. This was added drop-wise under constant stirring (Saleem *et al*., 2012). The resultant solution was stirred at 60 ˚C for 1 hour to yield a clear and homogeneous solution ready for coating. The resulting mixture was additionally stirred for 40 minutes to ensure that a homogeneous transparent solution is obtained. Finally, the solution centrifuged at 3500 rpm to remove unreacted materials (Musleh *et al*., 2018) and then filtrated using a standard 0.45µm filter paper(Alsaad *et al*., 2020).

Preparation of Al – doped ZnO (ZnO:Al)and B- doped ZnO (ZnO:B) Solutions

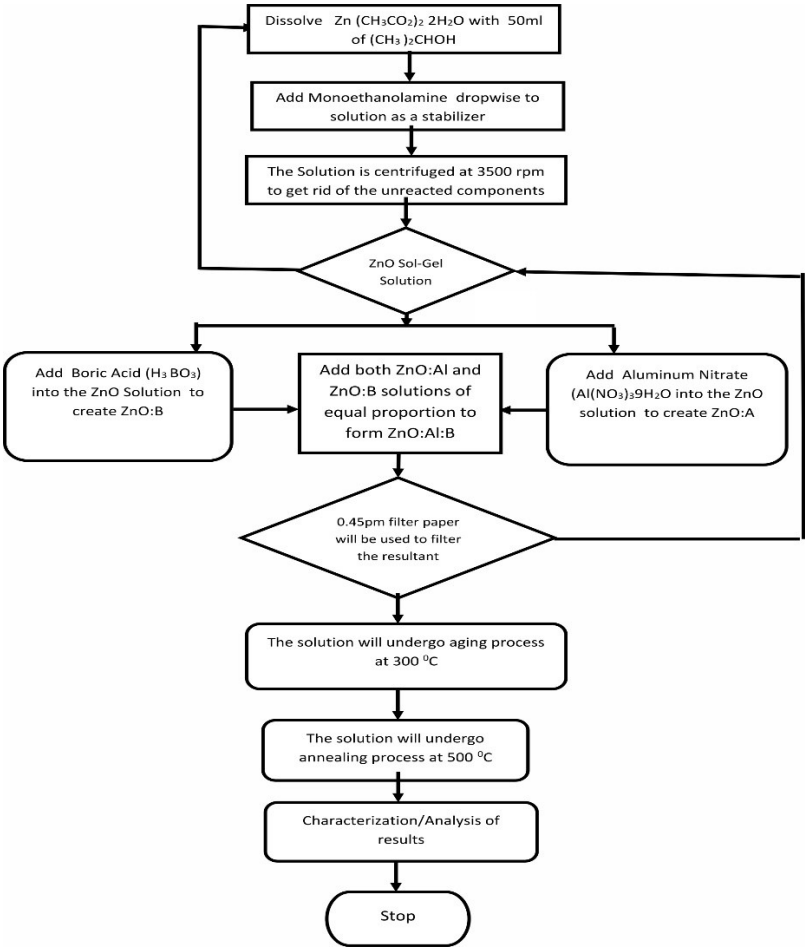
The next stage was the Preparation of Al- doped (ZnO:Al) and B- doped (ZnO:B) Solutions The process involved incorporating boric acid (2wt%) into the ZnO solution to create ZnO:B and aluminum nitrate (2wt%) into the ZnO solution to create ZnO:Al accordingly. Using a magnetic stirrer for 2 hours at 60 ^{0}C, a transparent solution for each of the doped systems was created. Lastly, 0.45µm filter paper was used to filter the resultant solution. At room temperature, the corresponding solution was swirled for two hours at 60 ^{O}C. This procedure was followed strictly to ensure the creation of solutions that can maintain a high degree of transparency.

Preparation of ZnO:Al:B Solutions

To prepare the ZnO:A:B both ZnO:Al and ZnO:B solutions was mixed of equal volumes. For hydrolysis and condensation, the corresponding solution was stirred for 2 hours at 60 ^{0}C. To allow for the aging process, the colorless, transparent, homogenous solution was kept at room temperature for 24 hours.

Pre –Heating and Post- Heating (Annealing)

The substrates were marked for identification on the reverse side of the surface to be coated. This was done so that the etching did not disturb the application of the solution. The substrates were cleaned by soap solution, chromic acid, distilled water, acetone, finally rinsed with deionized water and dried in an oven at 100 ^{0}C for 10 minutes. Having prepared the solutions with the desired properties, the substrates were then dipped in the solution for 2 hours using the dip-coating technique. This procedure is repeated 5 times to increase the thickness, dipping the glass substrate in the sol and withdrawing it at a rate of 0.9 cm/min at room temperature to prepare the gel films (Kaneva & Dushkin, 2011). The resulting films were then dried in an oven for 15 minutes at 200 ^{0}C to evaporate the solvent and the contaminated organic residues. The preheat treatment temperature is required for the complete evaporation of organics and the initiation of formation and crystallization of the ZnO film. (Sharmin *et al*., 2019). In order to obtain un-doped ZnO, B-doped ZnO, Al-doped ZnO and ZnO:Al:B thin films with the best possible crystalline structure, all films were annealed in air at 500 ^{0}C for 2 hours (Mursal *et al*., 2018). The complete experimental procedure is described in the flowchart of figure 1.



Figures 1: flowchart of the sol- gel method

RESULTS AND DISCUSSION

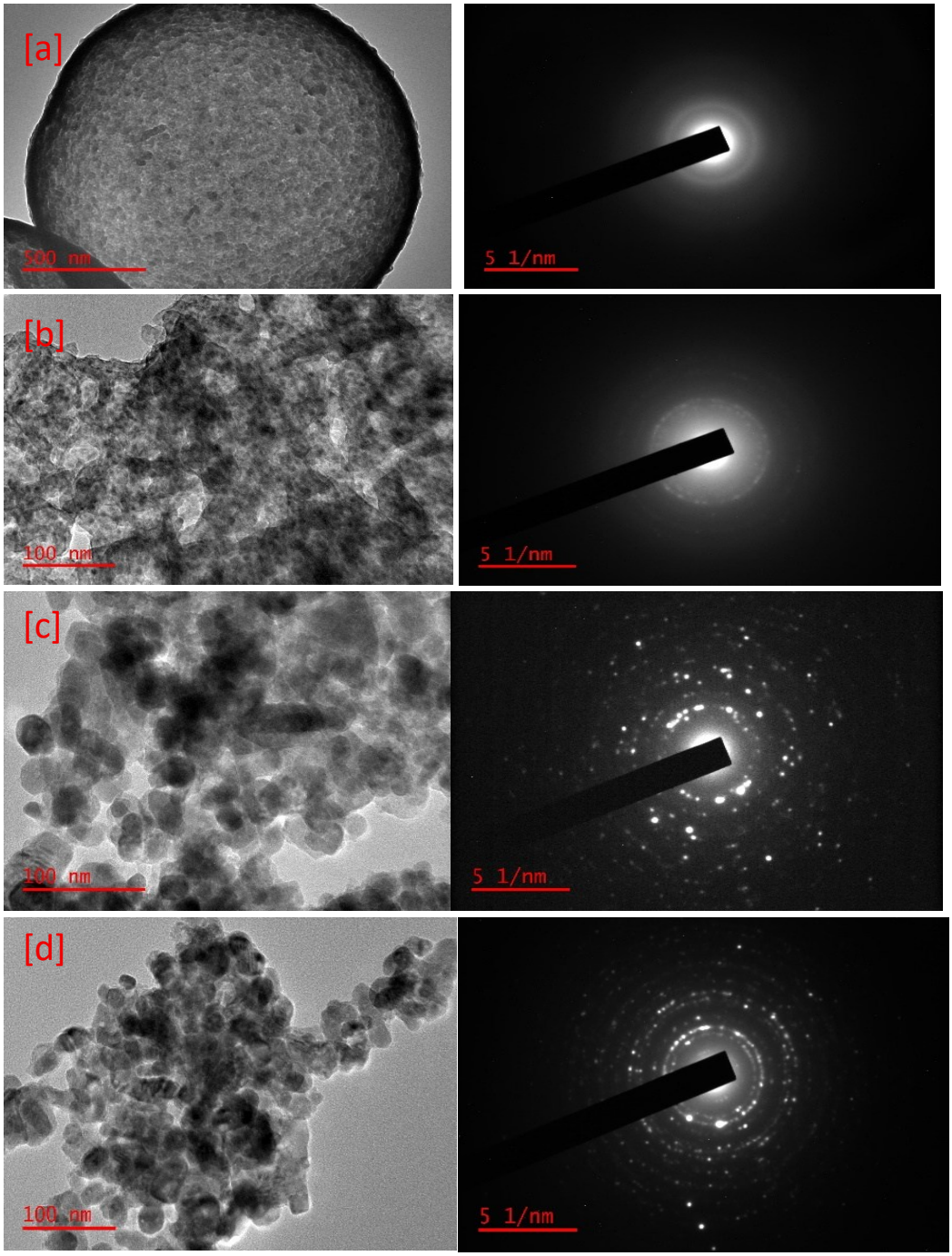


Figure 2: The HRTEM, SAED and Particle Size Distributions of (a) ZnO (b) ZnO:Al 2% (c) ZnO:B 2% (d) ZnO:Al 2%:B 2%

High-Resolution Transmission Electron Microscopy (HRTEM) Analysis

High-resolution transmission electron microscopy (HRTEM) was employed to investigate the morphology, crystallinity, and particle size distribution of the undoped and doped ZnO thin

films (Anantha Kumar et al., 2018). Indium tin oxide (ITO) serves as the established benchmark for microstructural quality in transparent conducting oxide systems, owing to its well-documented combination of controlled morphology, high crystallinity, and optimized optoelectronic performance (Kim et al., 2020; Park et al., 2019). In the present study, ITO thin films prepared under analogous sol-gel dip-coating conditions exhibited an average particle size of approximately 5–15 nm with sharp, well-defined SAED rings corresponding to the cubic bixbyite structure (Nicolescu et al., 2021). This combination of fine grain size and high crystalline perfection represents the gold standard against which the ZnO-based films were evaluated.

Undoped ZnO

The HRTEM micrograph of the undoped ZnO film (Fig. 2a) reveals predominantly spherical nanoparticles with a homogeneous size distribution. The average particle diameter, determined using ImageJ software, was 24.40 nm. This spherical morphology suggests controlled nucleation and growth conditions, characteristic of optimized sol-gel synthesis routes (Anantha Kumar et al., 2018). High-resolution imaging resolved distinct lattice fringes without observable distortion, confirming the highly crystalline nature of the films, consistent with observations by Abdelbaky et al. (2022). The selected area electron diffraction (SAED) pattern (inset, Fig. 2a) exhibits sharp, continuous rings indexed to the hexagonal wurtzite structure of ZnO, indicating polycrystalline nature with no detectable amorphous regions. Al-Qahtani et al. (2022) reported similar SAED patterns confirming phase-pure wurtzite ZnO. The homogeneous particle size distribution reflects a well-controlled production process, while the nanometer-scale dimensions (24.40 nm) provide a high surface-area-to-volume ratio suitable for diverse applications.

When benchmarked against ITO (5–15 nm), the undoped ZnO films exhibit significantly larger particle size (24.40 nm) and comparable SAED ring sharpness, indicating that while crystallinity is high, the morphological refinement characteristic of the gold standard ITO is not yet achieved in the undoped system.

ZnO:Al (Aluminum-Doped ZnO)

HRTEM examination of ZnO:Al films (Fig. 2b) revealed spherical morphology with a reduced average particle size of 20.48 nm compared to undoped ZnO (24.40 nm). This notable reduction indicates that Al^{3+} incorporation influences nucleation and growth kinetics, likely through the formation of point defects or inhibition of grain coalescence. The SAED patterns for ZnO:Al exhibited distinctly visible diffraction rings corresponding to the wurtzite structure, confirming preservation of the hexagonal crystal lattice. However, slight ring broadening was observed relative to undoped ZnO, suggesting the presence of lattice strain arising from the ionic radius mismatch between Al^{3+} (0.54 Å) and Zn^{2+} (0.74 Å) (Petrov et al., 2023). Sugitha et al. (2024) similarly reported that aluminum-doped ZnO films retain high crystallinity with clearly visible lattice fringes, consistent with the present observations.

Compared to ITO (5–15 nm), the ZnO:Al films (20.48 nm) demonstrate a partial reduction in particle size but remain larger than the gold standard. The reduced particle size relative to undoped ZnO enhances surface area, potentially improving properties such as adsorption, catalysis, and optical performance (Sugitha et al., 2024). The homogeneous spherical morphology further supports the suitability of these films for functional applications.

ZnO:B (Boron-Doped ZnO)

HRTEM analysis of ZnO:B thin films (Fig. 2c) revealed spherical nanoparticles with an average particle size of 23.83 nm, representing a modest reduction compared to undoped ZnO (24.40 nm). This decrease indicates that boron incorporation affects the growth and nucleation process, resulting in denser particles with increased surface area (Üzar et al., 2024). The SAED patterns for ZnO:B displayed diffraction rings characteristic of the wurtzite structure; however, increased ring broadening and more disordered diffraction spots were observed compared to undoped ZnO. This suggests greater structural disorder or enhanced lattice strain associated with the incorporation of the smaller-radius B^{3+} ion (0.27 Å) (Jeevarathinam & Asharani, 2024). The spherical morphology of ZnO:B nanoparticles contrasts with the slightly larger undoped ZnO particles, which exhibited more distinctive faceted structures due to unrestricted crystal growth on certain planes.

When compared to ITO (5–15 nm), the ZnO:B films (23.83 nm) exhibit substantially larger particle size and significantly broader SAED rings, indicating that while boron doping modifies morphology, it does not achieve the microstructural refinement characteristic of the gold standard. The observed structural disorder may alter the optical and electrical properties of the films, with implications for their performance in specific applications (Üzar et al., 2024).

ZnO:Al:B (Co-doped ZnO)

The HRTEM micrographs of ZnO:Al:B co-doped films (Fig. 2d) revealed predominantly spherical nanoparticles with an average particle size of 17.30 nm—the smallest among all ZnO-based films in this study. This represents a substantial reduction of approximately 29% relative to undoped ZnO (24.40 nm). The spherical morphology is consistent with homogeneous nucleation processes, potentially facilitated by Al acting as a stabilizer during synthesis. The significant size reduction suggests synergistic effects from dual doping, where Al^{3+} and B^{3+} collectively inhibit crystal growth through combined substitutional strain and grain boundary segregation mechanisms.

The SAED patterns for ZnO:Al:B maintained diffraction rings consistent with the wurtzite structure; however, noticeable ring broadening was observed, reflecting accumulated lattice strain from the dual dopant incorporation (Petrov et al., 2023; Jeevarathinam & Asharani, 2024). This indicates that while co-doping achieves superior morphological refinement, it may introduce increased lattice strain that could affect long-range crystallinity.

Critically, the ZnO:Al:B films (17.30 nm) approach the particle size range of the ITO gold standard (12–15 nm) more closely than any other ZnO-based film in this study. This represents

a significant achievement, demonstrating that co-doping strategies can yield ZnO-based TCOs with morphological characteristics approaching those of ITO. However, the broader SAED rings observed in the co-doped films indicate that this morphological refinement comes at the cost of increased lattice strain, highlighting the trade-off between grain size reduction and crystalline perfection.

Comparative Analysis and Mechanistic Discussion

The observed particle size trend—ZnO:Al:B (17.30 nm) < ZnO:Al (20.48 nm) < ZnO:B (23.83 nm) < undoped ZnO (24.40 nm)—reveals that the influence of dopants on ZnO grain growth is highly dependent on the specific dopant and their combination. Notably, the ranking differs from the typical expectation that boron, with its smaller ionic radius, would produce the smallest particles. The superior refinement achieved by co-doping suggests synergistic effects beyond simple ionic radius considerations.

The superior refinement in ZnO:Al:B (17.30 nm) compared to singly doped variants suggests that Al and B operate through complementary mechanisms: Al primarily through substitutional lattice strain, and B through grain boundary segregation (Petrov et al., 2023; Jeevarathinam & Asharani, 2024). Their combination yields cumulative growth inhibition. While ZnO:Al:B achieves particle size (17.30 nm) approaching that of ITO (5–15 nm), the observed SAED ring broadening indicates a trade-off: morphological refinement is accompanied by increased lattice strain and reduced crystalline perfection. This contrasts with ITO, which simultaneously achieves fine grain size and high crystalline quality (Kim et al., 2020; Park et al., 2019). Nevertheless, the significant particle size reduction achieved through co-doping positions ZnO:Al:B as a promising candidate for applications where ITO-like morphological refinement is desired, though optimization of annealing conditions may be necessary to mitigate strain-induced crystallinity degradation.

Hall Effect Measurement (Electrical Properties)

The electrical properties of undoped and doped ZnO thin films were evaluated using Hall effect measurements, with results summarized in Table 1. Indium tin oxide (ITO) serves as the established benchmark for transparent conducting oxide (TCO) electrical performance, typically exhibiting resistivity values in the range of $1–3 \times 10^{-4}$ Ω·cm, carrier concentrations of $5–10 \times 10^{20}$ cm^{-3}, and mobilities of 20–40 $cm^2/V·s$ depending on deposition conditions and annealing protocols (Kim et al., 2020; Park et al., 2019). These values provide a reference against which the performance of ZnO-based films can be evaluated.

Table 1: Electrical properties of ZnO, ZnO:Al, ZnO:B, and ZnO:Al:B thin films

Sample	Resistivity (ρ) (Ω·cm)	Hall Coefficient (R_H) (cm^3/C)	Carrier Concentration (n) (cm^{-3})	Mobility (μ) ($cm^2/V·s$)	Sheet Resistance (R_s) (Ω/sq)
ZnO	4.706×10^{-4}	-1.4×10^{-2}	4.5×10^{20}	29.5	19
ZnO:Al	4.26×10^{-4}	-1.247×10^{-2}	5.0×10^{20}	29.3	11.2

Sample	Resistivity (ρ) (Ω·cm)	Hall Coefficient (R_H) (cm³/C)	Carrier Concentration (n) (cm⁻³)	Mobility (μ) (cm²/V·s)	Sheet Resistance (R_s) (Ω/sq)
ZnO:B	4.4×10^{-4}	-1.95×10^{-2}	3.2×10^{20}	44	16
ZnO:Al:B	3.18×10^{-4}	-1.002×10^{-2}	6.2×10^{20}	31.7	8

Comparative Analysis of Electrical Properties

The Hall Effect measurements reveal distinct variations in electrical behavior across the undoped and doped ZnO thin films. All samples exhibited negative Hall coefficients, confirming n-type conductivity, which is characteristic of ZnO-based materials where oxygen vacancies and intrinsic defects serve as electron donors (Look et al., 2002).

Undoped ZnO

The undoped ZnO film exhibited a resistivity of 4.706×10^{-4} Ω·cm, a carrier concentration of 4.5×10^{20} cm⁻³, and a mobility of 29.5 cm²/V·s. These values are consistent with previously reported results for high-quality undoped ZnO thin films prepared by sol-gel methods (Abdelbaky et al., 2022). The relatively low resistivity indicates good crystallinity, which is supported by the HRTEM observations of sharp SAED rings and well-defined lattice fringes.

ZnO:Al (Aluminum-Doped)

Aluminum doping resulted in a reduction in resistivity to 4.26×10^{-4} Ω·cm and an increase in carrier concentration to 5.0×10^{20} cm⁻³ compared to undoped ZnO. This enhancement is attributed to the substitutional incorporation of Al^{3+} ions at Zn^{2+} lattice sites, which introduces additional free electrons into the conduction band (Ellmer, 2012). The mobility decreased slightly from 29.5 to 29.3 cm²/V·s, suggesting that the increase in carrier concentration was accompanied by minimal degradation of crystal quality. This observation aligns with the HRTEM results, which showed preservation of the wurtzite structure with only slight SAED ring broadening.

ZnO:B (Boron-Doped)

Boron-doped ZnO exhibited a resistivity of 4.4×10^{-4} Ω·cm, a carrier concentration of 3.2×10^{20} cm⁻³, and notably high mobility of 44 cm²/V·s. The elevated mobility, which is the highest among all samples, suggests effective charge transport with reduced scattering centers. However, the carrier concentration is the lowest among the doped samples, indicating that boron may be less efficient than aluminum in substituting at Zn^{2+} sites due to its significantly smaller ionic radius (B^{3+}: 0.27 Å vs. Zn^{2+}: 0.74 Å) (Üzar et al., 2024). This observation is consistent with the HRTEM findings, where ZnO:B exhibited increased SAED ring broadening indicative of lattice strain and structural disorder.

ZnO: Al:B (Co-doped)

The co-doped ZnO:Al:B sample demonstrated the most favorable electrical properties among all samples, with a resistivity of 3.18×10^{-4} Ω·cm, a carrier concentration of 6.2×10^{20} cm⁻³,

a mobility of 31.7 $cm^2/V \cdot s$, and the lowest sheet resistance of 8 Ω/sq. This represents a 32% reduction in resistivity compared to undoped ZnO and a 25% reduction compared to singly doped ZnO:Al. The simultaneous increase in both carrier concentration and mobility, despite the general trade-off between these parameters, suggests a synergistic effect from co-doping (Koralli et al., 2022; Petrov et al., 2023).

Benchmarking Against ITO Gold Standard

To contextualize the performance of the developed ZnO-based films, their electrical properties are compared against ITO, the industry standard for TCO applications.

Table 2: Benchmarking Against ITO Gold Standard

Parameter	ITO (Gold Standard)	ZnO:Al:B (This Work)	ZnO:Al	ZnO:B	Undoped ZnO
Resistivity (Ω·cm)	$1–3 \times 10^{-4}$	**3.18×10^{-4}**	4.26×10^{-4}	4.4×10^{-4}	4.706×10^{-4}
Carrier Concentration (cm^{-3})	$5–10 \times 10^{20}$	**6.2×10^{20}**	5.0×10^{20}	3.2×10^{20}	4.5×10^{20}
Mobility ($cm^2/V \cdot s$)	20–40	**31.7**	29.3	44	29.5
Sheet Resistance (Ω/sq)	5–15	**8**	11.2	16	19

The ZnO: Al:B co-doped film achieves a resistivity of 3.18×10^{-4} Ω·cm, which falls within the lower range of the ITO benchmark ($1–3 \times 10^{-4}$ Ω·cm) (Kim et al., 2020). The carrier concentration of 6.2×10^{20} cm^{-3} is well within the optimal range for TCOs, while the mobility of 31.7 $cm^2/V \cdot s$ demonstrates effective charge transport comparable to high-quality ITO. The sheet resistance of 8 Ω/sq is particularly noteworthy, as it approaches the values typically required for transparent electrode applications in photovoltaic devices (Green et al., 2023).

Implications for Photovoltaic Applications

The combination of low resistivity (3.18×10^{-4} Ω·cm), high carrier concentration (6.2×10^{20} cm^{-3}), and low sheet resistance (8 Ω/sq) positions the ZnO:Al:B co-doped thin film as a promising candidate for transparent electrode applications in photovoltaic solar cells. These values are comparable to those of ITO, which is widely used as a transparent conducting oxide in devices such as organic photovoltaics, perovskite solar cells, and thin-film silicon solar cells (Kim et al., 2020).

The sheet resistance of 8 Ω/sq is particularly significant, as window layer applications typically require sheet resistance values below 10–15 Ω/sq to minimize series resistance losses (Green et al., 2023). Furthermore, the high carrier concentration ensures sufficient free carrier density for effective charge collection, while the mobility of 31.7 $cm^2/V \cdot s$ supports efficient lateral charge transport.

Based on these findings, the ZnO:Al:B co-doped thin film can be considered a viable alternative to ITO in photovoltaic solar cell applications, offering comparable electrical

performance with the added advantages of lower material cost and greater elemental abundance (Ellmer, 2012; Koralli et al., 2022).

CONCLUSION

This research successfully synthesized and characterized aluminum and boron co-doped zinc oxide (ZnO) thin films using the sol-gel dip-coating method for potential application as a window layer in photovoltaic devices. The findings demonstrate that co-doping with Al and B significantly refines the particle size of ZnO, with the ZnO:Al:B film exhibiting the smallest average particle size of 17.30 nm. The ZnO-based material approaches the benchmark performance of indium tin oxide (ITO) thanks to this decrease in particle size. Crucially, the ZnO:Al:B co-doped film's electrical characteristics show great promise. These properties are similar to those of high-quality ITO, with resistivity of 3.18×10^{-2} Ω•cm, carrier concentration of $6.2 \times 10^{2\circ}$ cm^{-3}, and mobility of 31.7 $cm^2/V•s$. Particularly noteworthy is the resulting sheet resistance of 8 Ω/sq, which satisfies the crucial need for effective transparent electrodes in solar cells. These findings strongly imply that Al and B co-doped ZnO films are a competitive substitute for ITO, providing similar optoelectronic performance together with the inherent benefits of increased material abundance and cheaper cost.

RECOMMENDATIONS

Even though both Al and B showed a notable improvement with 2wt% doping, more research into adjusting the aluminum and boron doping concentrations is advised. This could result in even more precise optoelectronic property adjustment and even performance that surpasses the existing benchmark. It will be better to create a real solar cell devices with window layers made of the optimal ZnO:Al:B films. To evaluate these devices' practical effectiveness, long-term stability, and overall performance versus cutting-edge ITO-based devices, extensive testing under typical illumination settings is essential. Investigating alternative deposition methods, such as sputtering or chemical vapor deposition, for Al and B co-doped ZnO films could offer more insights and possibly result in further improvements in film quality and uniformity, even though the sol-gel dip-coating method proved successful and economical.

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