Faculty of Natural and Applied Sciences Journal of Applied Chemical Science Research
Print ISSN: 3027-0359
www.fnasjournals.com
Volume 2; Issue 3; May 2025; Page No. 16-30.

Zinc Oxide Co-Doped with Aluminium and Boron (Al:B:ZnO) Thin Films via Sol–Gel Process for Solar Cell Window Layers: A Review

***Ewansiha, K.O., Ewansiha,A.O., Ewansiha, C.E., & Ayo, S.A.**
Department of Physics, Federal Polytechnics Bida, Niger State

***Corresponding author email**: kingsleyewansiha74@gmail.com

Abstract
Solar energy is the most economical and plentiful long-term natural resource currently accessible. The rate of global economic growth and technical advancement is increasingly dependent on the need for cost-effective, high-performance optoelectronic devices. Zinc oxide (ZnO) films have garnered significant interest as viable substitutes for traditional transparent conductive oxides (TCOs) in solar systems. Zinc oxide nanoparticles (ZnONPs) are among the most extensively used metal oxide nanoparticles, garnering international scientific attention owing to their distinctive optical and chemical properties, biocompatibility, low toxicity, sustainability, and cost-effectiveness. The adaptability of ZnO enables doping with transition metals to improve its structural, electrical, optical, and magnetic properties. Doping with aluminium (Al) enhances electrical conductivity and optical clarity, while boron (B) doping reduces electrical resistivity and optical bandwidth while augmenting carrier concentration. Doping with a single element often improves just one specific optical or electrical characteristic. Simultaneous doping with both Al and B mitigates this constraint, resulting in a synergistic action that improves optical and electrical characteristics. . After receiving Al-B co-doping treatment, the resistivity of ZnO film dropped from 6.12×10^{2} Ωcm to 2.07×10^{-4} Ωcm. Furthermore, the ZnO film's transmittance values, surface homogeneity, and figure of merit value significantly increased due to the presence of Al and B components. Every investigation shown that the advantageous physical features of Al–B co-incorporated ZnO films make them a viable substitute for ITO films in TCO applications. The simultaneous enhancement renders co-doped ZnO very appropriate for transparent conductive electrodes and window layers in solar cell applications.

Keywords: Zinc Oxide, Sol-Gel, Transparent Conductive Oxide, Doping, Solar Cells

Introduction

Energy is the essence of contemporary society. The economic prosperity and scientific progress of any nation are contingent upon it (Alsagri, 2022). The escalating rates of population growth, industrial expansion, and per capita energy consumption are the primary factors that will drive a rise in energy demand in the next years. Traditional energy sources are becoming unreliable and unsustainable, while global oil reserves are inadequate for sustained reliance. As a result, the pursuit of sustainable and renewable energy alternatives that are cost-effective and environmentally friendly has become a major focus (Hassan & Mohamad, 2012). The negative consequences of using non-renewable energy on human health and the environment have driven researchers to seek greener alternatives. Unlike fossil fuel-based energy generation, solar energy production results in minimal emissions of greenhouse gases and other harmful pollutants during operation (Li et al., 2019). Numerous renewable energy sources, including geothermal, hydro, solar, and wind, have become attractive choices for creating cleaner, more sustainable energy systems. Due of its enormous potential for harnessing solar energy, solar energy has garnered a lot of attention among these (Holechek et al., 2022). Solar power holds the unique advantage of being applicable even in environments where other renewable sources may be impractical, including areas beyond Earth's surface (Neha & Rambeer, 2021). Consequently, research and development in solar energy technologies have rapidly expanded, leveraging the resource's abundant, free, and environmentally beneficial nature.

The use of photovoltaic systems has become an effective strategy for converting sunlight into electricity through efficient light absorption, a process enabled by solar cells, which play a fundamental role in this transformation (Pastuszak & Węgierek, 2022). The absorber layer of solar cells, which made up the original generation of solar

Cite this article as:
Ewansiha, K.O., Ewansiha,A.O., Ewansiha, C.E., & Ayo, S.A. (2025). Zinc Oxide co-doped with Aluminium and Boron (Al:B:ZnO) thin films via sol–gel process for solar cell window layers: A review. *FNAS Journal of Applied Chemical Science Research, 2*(3), 16-30.

cells, has traditionally been made mostly of silicon (Si), especially when producing them on a big scale. Developments in research have produced substitute materials with improved fundamental characteristics, such as cadmium telluride (CdTe) and copper indium gallium selenide (CIGSe). These newer materials feature tunable band gaps, higher absorption coefficients (approximately 10^5 cm^{-1}), and require only thin layers (about 1–3 μm), with some degree of flexibility (Doroody et al., 2022). With the emergence of these alternatives to Si, it becomes essential to ensure efficient transmission of sunlight to the absorber layer and effective collection of generated charge carriers to reduce energy losses (Regmi et al., 2023). This requires the use of highly effective transparent conductive oxides (TCOs), typically consisting of oxide-based materials. When applied as thin films, TCO coatings' exceptional electrical conductivity and transparency in the visible light spectrum make them particularly useful in photovoltaic and transparent electronics (Gultepe & Atay, 2022). Because of their special blend of optical transparency and electrical conductivity, TCOs serve a variety of purposes.

They are widely used as electrical contacts in devices such as solar cells and light-emitting diodes (Chavan et al., 2023). Two common transparent conductive oxides (TCOs) in industrial applications are indium tin oxide (ITO) and fluorine-doped tin oxide (FTO). Because of its remarkable conductivity and transparency, which are essential for maximising photovoltaic efficiency, indium tin oxide (ITO) is used as the top layer in thin-film solar cells (Farsi et al., 2021). ITO maintains good transparency even with reduced thickness and exhibits relatively low resistivity. Due to the high expense and potential health concerns linked to the use of indium, along with the challenges associated with fluorine during the deposition of FTO, there has been a growing interest in exploring alternative transparent conductive oxide (TCO) materials. Ideal substitutes should be flexible, environmentally friendly, require low-temperature fabrication processes, and maintain stable electrical conductivity even under mechanical stress such as bending or stretching. Zinc oxide (ZnO) has emerged as a strong candidate, showing promise as an effective replacement for ITO (Koralli et al., 2022). Various nanomaterials exhibit properties suited for different layers in solar cells. Among them, zinc oxide has attracted significant research attention. With lattice parameters of a = 0.325 nm and b = 0.521 nm, ZnO has a stable wurtzite crystal structure and is non-toxic, which makes it ideal for solar applications (Shweta & Thapa, 2019). Its attractive qualities, including great chemical and thermal stability, affordability, and a broad direct band gap, make it one among the most researched semiconductor oxides, allowing potential applications in a variety of technological domains (Amakali et al., 2020). Furthermore, ZnO has a centrosymmetric structure, which grants it the highest tensor among semiconductors and allows for strong electromechanical coupling (Haq et al., 2017). ZnO has remarkable properties at the nanoscale that make it appropriate for a wide range of applications, such as surface acoustic wave devices, gas and biosensors, solar cells, photodetectors, photocatalysts, ultraviolet nano-lasers, and nanogenerators (Shweta & Thapa, 2019). Products such as batteries, ferrites, ceramics, glass, cement, lubricants, paints, adhesives, plastics, sealants, and nutritional supplements are made using it in combination with other compounds (Orori, 2023). Particle size, shape, pH, and biocompatibility are some of the variables that affect ZnO's efficacy in various applications; the synthesis method used has a significant impact on the structure of the material. The main goal of photovoltaic (PV) technology is to convert sunlight directly into electrical power without the need for a conversion step in between.

1. Solar Cells

Solar cells are composed of semiconductor materials that convert energy packets, known as photons, into electrical energy. When photons strike the semiconductor, electrons within the crystal lattice can break free from their atomic bonds, leading to electricity generation (Prasetyo et al., 2023). The fundamental component of a photovoltaic (PV) system is a photovoltaic (PV) solar cell, which is made by combining two thin layers of different semiconductor types—one negatively charged (N-type) and the other positively charged (P-type)—both of which have the ability to absorb solar energy as shown in figure 1 (Andjela, 2021). PV cells are typically produced using silicon-based semiconductors, such as polycrystalline silicon (pc-Si), monocrystalline silicon (c-Si), and amorphous silicon (a-Si). Polycrystalline silicon modules are mostly used in terrestrial systems (Vignesh et al., 2022). Recent market introductions include advanced materials such as cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and dye-sensitized solar cells (DSSCs). Notwithstanding these advancements, silicon-based modules continue to prevail owing to their superior efficiency, extended lifetime, resilience, and economic viability (Huang et al., 2021). A conventional thin-film solar cell generally comprises a severely doped layer on a substrate, onto which a moderately doped absorber layer is applied. Over this absorber, a highly doped layer with the opposite conductivity type is added to act as the emitter or window layer (Bin Rafiq et al., 2020). The materials selected for each layer in a solar cell can differ, and manufacturers of CIGS modules have employed slightly varied configurations over time, though the overall device architecture remains consistent (Larsson, 2020). The transparent front contact layer plays a critical role in transporting electrical current laterally to the metal grid. Its effectiveness depends on two key properties: high optical transparency and strong lateral conductivity. Consequently, several transparent conducting oxides (TCOs) are used, with aluminum-doped zinc oxide (AI:ZnO) being among the most often employed.

Cite this article as:
Ewansiha, K.O., Ewansiha,A.O., Ewansiha, C.E., & Ayo, S.A. (2025). Zinc Oxide co-doped with Aluminium and Boron (Al:B:ZnO) thin films via sol–gel process for solar cell window layers: A review. *FNAS Journal of Applied Chemical Science Research, 2*(3), 16-30.

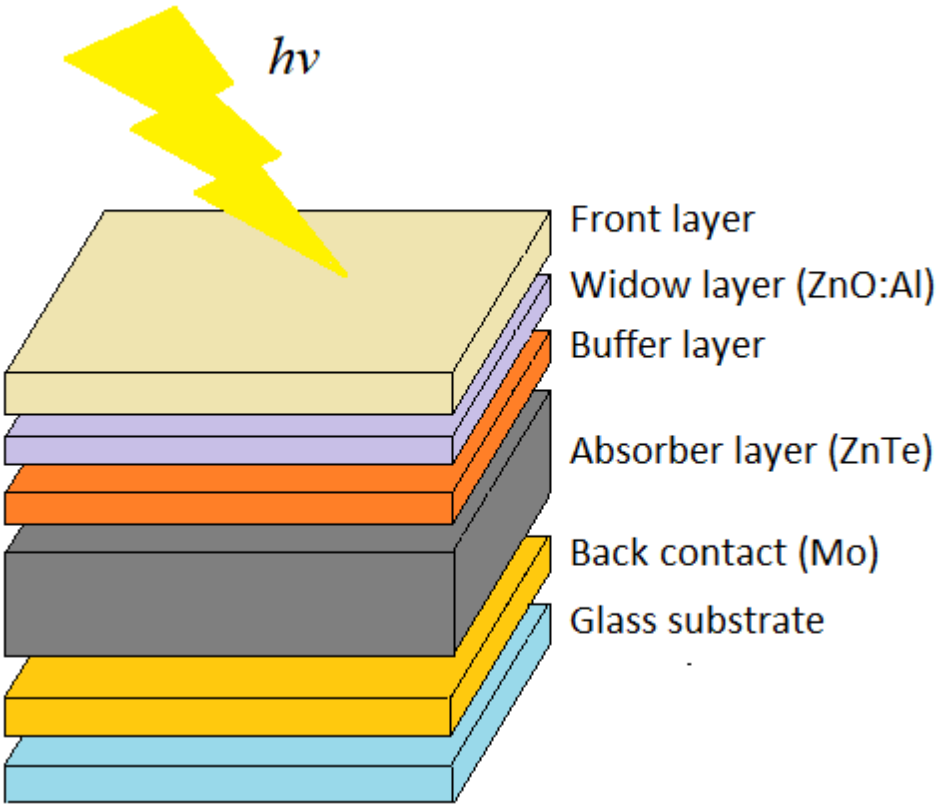


Figure 1: Schematic arrangement of a thin film-based solar cell layers (Zyoud et al., 2021)

2. Transparent Conductive Oxide (TCO)?

TCOs are typically n-type semiconductors that are severely doped. It can be difficult to simultaneously achieve high conductivity and transparency (Calnan & Tiwari, 2010). One of the many desirable properties of ZnO, an n-type semiconductor, is its direct wide band gap of 3.37 eV at room temperature, which makes it appropriate for a variety of optical applications. Additionally, it possesses a 60 meV exciton binding energy, which is exceptionally high and beneficial for the construction of different optoelectronic devices (Alsaad et al., 2020). In addition, compared to single Al doping, co-doping ZnO with aluminum and boron (Al:B) improves its optical, physical, and electrical characteristics. The co-doping reduces the resistivity of the ZnO film and enhances its transmittance, surface uniformity, and overall efficacy, establishing it as a formidable alternative to indium tin oxide (ITO) in transparent conductive oxide (TCO) applications (Gultepe & Atay, 2022). Boron-doped ZnO (ZnO:B) thin films exhibit superior transparency compared to their undoped counterparts. These doped films also exhibit higher optical band gaps and Urbach energies, parameters often used to assess the electronic quality of thin films in solar absorber layers (Naser et al., 2022).

Because of their exceptional conductivity and transparency in thin film configurations under visible light, transparent conducting oxides (TCOs) are highly valued in photovoltaic and transparent electronics applications. When selecting the most suitable TCO material, factors such as raw material availability and the cost-effectiveness of the deposition process play critical roles. A well-informed selection process involves balancing various performance parameters while also considering cost, rather than focusing solely on maximizing conductivity and transparency, which can lead to suboptimal outcomes (Castañeda, 2022). A popular TCO, indium tin oxide (ITO) has achieved commercial success in solar applications because of its low resistivity (about 10^{-4} **Ω•**cm) and high transparency (over 85%) (Gultepe & Atay, 2022). Despite its popularity, concerns about indium's limited availability, toxicity, and poor stability in the reducing environments typical of solar cell fabrication have driven the search for alternatives (Sarma et al., 2019). As a result, efforts have been directed toward developing new, cost-effective TCOs or improving existing materials with minimal or no indium content. One potential replacement for ITO is zinc oxide (ZnO). Chemical, biological, and gas sensors, optical and electrical devices,

Cite this article as:
Ewansiha, K.O., Ewansiha,A.O., Ewansiha, C.E., & Ayo, S.A. (2025). Zinc Oxide co-doped with Aluminium and Boron (Al:B:ZnO) thin films via sol–gel process for solar cell window layers: A review. *FNAS Journal of Applied Chemical Science Research, 2*(3), 16-30.

display window materials, thermal barriers, piezoelectric transducers, solar cells, varistors, laser technologies, and drug delivery systems are just a few of the many uses for this multipurpose material (Khantoul et al., 2018). One of ZnO's key advantages over ITO is that it is composed of earth-abundant elements, eliminating concerns about material scarcity. Its inherently high electrical resistivity poses a challenge, limiting its effectiveness in photovoltaic applications and making it less competitive with ITO in certain scenarios.

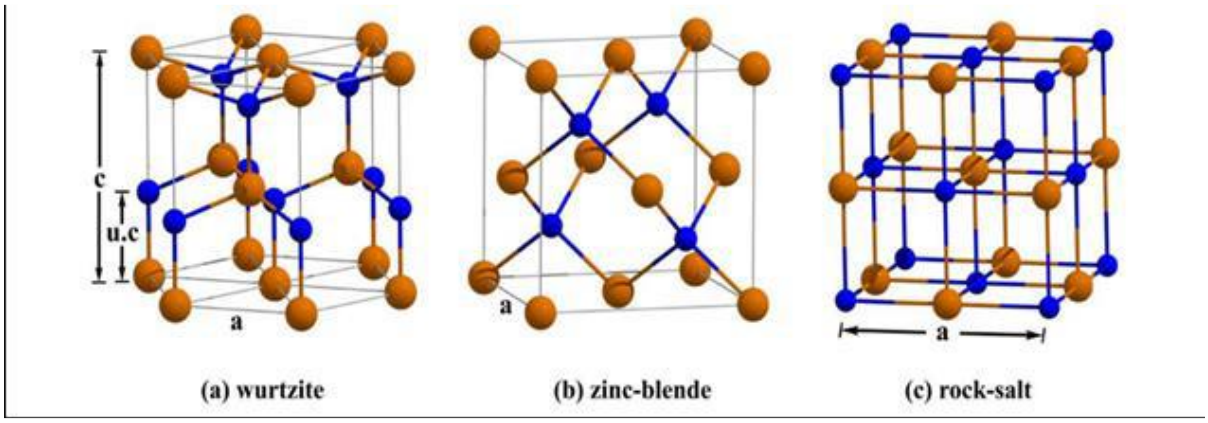


Figure 2: Zinc oxide crystals (Naser et al., 2022)

Zinc Oxide (ZnO) Nanoparticles

New developments in nanotechnology have made it easier to produce materials at the nanoscale with special physicochemical characteristics that may be used in a wide range of technical and biological applications. Because of their unique properties that differ significantly from those of their bulk counterparts, metal oxide nanoparticles (MONPs) have attracted a lot of attention (Negrescu et al., 2022). In the field of photovoltaics, thin film technologies have emerged as promising alternatives capable of enhancing device performance (Sivaraj et al., 2022). The improved electrochemical activity, thermal conductivity, and nonlinear optical features of nanoparticles make them particularly appealing since they open up a range of new uses. By altering their shape and structure, zinc oxide nanoparticles (ZnO-NPs) may be made to have unique optical and chemical characteristics (Mandal et al., 2022). In materials science, ZnO is appreciated for its mechanical stability and strong luminescence at room temperature. As an II–VI semiconductor, ZnO exhibits mainly covalent bonding with a significant ionic component. Its high theoretical capacity, environmental sustainability, cost-effectiveness, and availability make it a strong candidate for use as an anode material in lithium-ion batteries. Its characteristics make it advantageous for room-temperature ultraviolet lasing and various applications, including optoelectronics, spintronics, Ultraviolet light emitters, varistors, thermistors, transparent power electronics, acoustic wave devices, piezoelectric transducers, sensors, solar cells, and energy-harvesting nanogenerators (Bhandari et al., 2023). The effective emission of ZnO renders it essential for solid-state lighting technologies and facilitates the development of novel optical and magnetic devices, such as spin-polarized solar cells, spin-LEDs, and magneto-optical switches. ZnO has an optical band gap of 3.37 eV at ambient temperature, a resistivity of around 10^{-2} Ω•cm, and electron mobility between 10 and 60 $cm^2 \bullet V^{-1} \bullet s^{-1}$, contingent upon its microstructure. ZnO may structurally manifest in three crystalline forms: rocksalt (cubic), zinc blende (face-centered cubic), and wurtzite (hexagonal), as shown in figure 2 with the latter exhibiting the highest stability during production. At the nano- and microscale, ZnO exhibits a diverse array of morphologies, including nanorods, nanotubes, nanorings, nanosprings, nanospirals, nanohelices, nanobows, branched nanowires, and nanowalls (Nourdine et al., 2021). ZnO nanoparticles exhibit non-toxicity and biocompatibility, with functional characteristics influenced by factors like size, shape, orientation, and aspect ratio (Negrescu et al., 2022). Diverse nanomaterials are tailored for certain components of solar cells, with ZnO integrated into many layers of these cells. ZnO, in its powdered form, is insoluble in water and exhibits several distinctive characteristics. ZnO has been used in the manufacture of batteries, ceramics, glass, cement, lubricants, adhesives, paints, plastics, and dietary additives when mixed with other chemicals. Its role in optoelectronic applications include the generation of emission and spintronic devices,

Cite this article as:
Ewansiha, K.O., Ewansiha,A.O., Ewansiha, C.E., & Ayo, S.A. (2025). Zinc Oxide co-doped with Aluminium and Boron (Al:B:ZnO) thin films via sol–gel process for solar cell window layers: A review. *FNAS Journal of Applied Chemical Science Research, 2*(3), 16-30.

sensors, and photovoltaic components. ZnO has been used as a buffer layer in Copper-Indium-Gallium-Selenide (CIGS) solar cells, with recent experimental studies analysing the effect of ZnO layer thickness on the power output of solar cells constructed using this nanomaterial (Orori, 2023).

3. Doping of ZnO Nanoparticles

The rising demand for cost-effective and high-performance optoelectronic devices has driven the development of more efficient transparent conductive oxide (TCO) thin films, particularly for use in solar cells, liquid crystal displays, heat-reflective coatings, photothermal systems, gas sensors, optical sensors, and acoustic wave devices. Zinc oxide (ZnO) has become a leading candidate among various transparent conductive oxide (TCO) materials due to its exceptional optical and electrical properties, chemical and mechanical durability, and natural abundance, making it a more economical alternative to commonly used materials like indium tin oxide (ITO) and tin oxide (SnO_2). Pure ZnO thin films often exhibit insufficient thermal stability. This limitation can be addressed through doping, which not only enhances thermal stability but also boosts the electrical conductivity of the films. Doping is often accomplished by replacing Zn^{2+} ions with higher-valence cations as indium, aluminium, or gallium. The efficacy of a dopant is contingent upon characteristics such as its electronegativity and the dimensional disparity between the dopant ion and the zinc ion (Nunes et al., 2002). The incorporation of cations from groups IIIA, IIIB, IVA, and IVB, or non-metal anions, has markedly enhanced the conductivity and transparency of ZnO films. Elements such as boron, aluminum, gallium, indium, yttrium, titanium, zirconium, silicon, tin, and fluorine have all been employed in various doping processes. One promising strategy to further enhance the electrical properties of ZnO thin films is co-doping, where two elements are introduced simultaneously. This technique has been shown to reduce resistivity more effectively than single-element doping. Aluminum is commonly used in these co-doping combinations, including pairs like B–Al, In–Al, Ga–Al, Sn–Al, Sc–Al, Ti–Al, V–Al, Mg–Al, Ni–Al, and Ag–Al (Gultepe & Atay, 2022). To date, over 20 different elements have been explored for doping ZnO-based materials, with aluminum (Al), gallium (Ga), and magnesium (Mg) being among the most extensively studied. For instance, gallium doping has been found to decrease resistivity ($\sim 1.23 \times 10^{-4}\ \Omega\cdot$cm) while reducing carrier mobility (30.4 $cm^2/V\cdot s$). Aluminum doping, on the other hand, enhances transmittance and introduces more charge carriers by occupying Zn sites. ZnO's properties can be optimized by managing oxygen content in its hexagonal crystal structure. Fluorine is often used to substitute oxygen atoms in order to minimise flaws. Fluorine, owing to its elevated electronegativity, mitigates carrier entrapment, thereby enhancing carrier mobility. Fluorine doping introduces supplementary electrons that diminish resistivity and enhance carrier concentration in transparent conductive oxide (TCO) thin films. It also reduces light absorption due to oxygen-related flaws in ZnO, hence augmenting the material's optical band gap and enhancing transmittance, especially in the longer wavelength spectrum (Jang et al., 2023). Single-element doping typically improves either optical or electrical properties, but not both, to a significant extent. Recent findings indicate that incorporating two or more dopants simultaneously can yield better results. For instance, co-doping ZnO with magnesium and gallium (MgZnO) demonstrates a synergistic enhancement; magnesium widens the band gap and boosts optical performance, while gallium enhances electrical characteristics. Similarly, combining a metal dopant with fluorine has shown greater benefits than using a metal alone. Investigations on co-doping with elements such as copper (Cu), manganese (Mn), cobalt (Co), and titanium (Ti) indicate that these metals facilitate the regulation of zinc vacancies within the ZnO lattice, hence enhancing both electrical and optical characteristics. The synergistic effects of fluorine and metal co-doping in ZnO thin films are yet inadequately investigated (Jang et al., 2019).

The choice of dopant type and concentration is crucial for optimising the material's characteristics for certain applications. For example, aluminum-doped ZnO exhibits enhanced conductivity and optical clarity, making it suitable for use in transparent electrodes and photovoltaic devices (Badgujar et al., 2022). Indium doping improves both electrical performance and thermal stability, which is advantageous for applications like gas sensors and transparent conductors (Sohn & Soo, 2011). Copper doping boosts photocatalytic efficiency, useful in water and air purification (Khalid et al., 2022). While silver doping not only improves photocatalytic activity but also imparts antibacterial properties, making it effective in environmental and biomedical uses (Wagh et al., 2023). Titanium-doped ZnO is known for enhanced photocatalytic activity and structural stability, making it applicable in wastewater treatment and solar energy systems (Sarathi et al., 2022). Nitrogen doping has shown improvements in conductivity, optical behavior, and sensitivity for environmental sensing and energy-related applications (Sun et al., 2013). Lithium-doped ZnO offers better electrical performance and heat resistance, making it ideal for transparent conductive layers and electronic components (Zhao et al., 2019). Magnesium-doped ZnO has been found to enhance optical properties and thermal stability, making it suitable for use in optoelectronics and solar cells (Rouchd et al., 2017). Chromium-doped ZnO exhibits improved magnetic properties, along with increased photocatalytic activity and gas sensing capabilities, making it ideal for magnetic storage devices, environmental sensors, and photocatalytic applications (Alkallas et al., 2022). Similarly, manganese-doped ZnO demonstrates

Cite this article as:
Ewansiha, K.O., Ewansiha,A.O., Ewansiha, C.E., & Ayo, S.A. (2025). Zinc Oxide co-doped with Aluminium and Boron (Al:B:ZnO) thin films via sol–gel process for solar cell window layers: A review. *FNAS Journal of Applied Chemical Science Research, 2*(3), 16-30.

enhanced magnetic properties, along with improved photocatalytic and gas sensing activities, and can be used in magnetic storage, environmental sensors, and photocatalysis (Thakur et al., 2020). Aluminium and boron co-doped ZnO films, produced by spin coating, provide a substitute for ITO films often used in solar cell applications. The aluminum-to-boron doping ratio remained constant, while boron was introduced at varying rates. The co-doping method markedly enhanced the optical, surface, and electrical properties of the ZnO films, making them exceptionally appropriate for transparent conductive oxide (TCO) applications. The resistivity of the ZnO film diminished from 6.12×10^{2} Ωcm to 2.07×10^{-4} Ωcm as a result of the Al-B co-doping treatment, concurrently enhancing the transmittance, surface uniformity, and figure of merit value. The findings suggest that Al-B co-doped ZnO films might serve as a viable substitute for ITO films in transparent conductive oxide applications (Gultepe & Atay, 2022). Co-doping ZnO materials with non-metal elements such as nitrogen (N) or sulphur (S) may enhance their characteristics. Nitrogen and aluminium co-doped ZnO exhibits improved photocatalytic activity and gas detecting capabilities, beneficial for environmental sensors and photocatalysis (Dutta et al., 2009). Co-doping with transition metals like manganese (Mn) or cobalt (Co) may impart magnetic characteristics to ZnO and improve its photocatalytic and gas sensing functionalities. Manganese and silver co-doped ZnO has enhanced photocatalytic activity and antibacterial characteristics, making it advantageous for water purification and biomedical applications (Tang et al., 2013). Co-doping with rare-earth elements such as cerium (Ce) or lanthanum (La) may enhance the optical and photocatalytic characteristics of ZnO. Cerium and nitrogen co-doped ZnO has shown improved photocatalytic activity and stability, rendering it appropriate for wastewater treatment and solar energy applications (Costa-Silva et al., 2022). The selection of dopants and their concentrations in co-doped ZnO materials need meticulous optimisation to get the requisite characteristics for particular applications. Co-doping is a viable approach to attain synergistic effects, optimising the properties of ZnO for diverse applications. The doping concentration in ZnO materials significantly influences their properties. At low concentrations, dopant atoms are sparsely distributed, leading to minimal impact on the material's properties. As the doping concentration increases, the dopants become more concentrated, and their influence on the material's characteristics becomes more noticeable (Carofiglio et al., 2020). The concentration of dopants affects various properties, including electrical conductivity. At low doping concentrations, conductivity may improve due to the introduction of charge carriers, while higher doping concentrations can reduce conductivity due to the formation of defects and scattering of charge carriers.

The doping concentration of ZnO materials can influence their optical properties, including absorption and emission spectra. At low doping levels, the optical properties may remain relatively unaffected, but at higher doping concentrations, significant changes can occur due to the formation of energy levels associated with the dopants (Mishra et al., 2022). In terms of photocatalytic activity, which is important for applications like water and air purification, the doping concentration can enhance the material's photocatalytic properties. Increased doping levels lead to a higher density of dopant-related defects, thereby improving the material's photochemical performance (Sun et al., 2023). Doping concentration can also affect the magnetic properties of ZnO materials, which are important for magnetic storage applications. The inclusion of magnetic dopants, such as manganese (Mn) or cobalt (Co), can increase the density of magnetic ions, thus enhancing the material's magnetic properties (Chakraborty & Shaik, 2019). Regarding thermal stability, doping can influence the material's ability to withstand high temperatures. At low doping concentrations, thermal stability may remain relatively unaffected, but higher doping levels can introduce lattice strain, which may reduce thermal stability (Dao & Makino, 2021). For biocompatibility, doping can alter the toxicity and biological compatibility of ZnO materials, which is vital for biomedical applications like drug delivery systems. Dopants such as magnesium (Mg) or lithium (Li) can improve the biocompatibility of ZnO by reducing its toxicity and enhancing its interaction with biological systems (Oleshko et al., 2020). Doping can also impact the structural properties of ZnO, including its crystal structure and morphology. The introduction of dopants can cause lattice strain and affect the growth dynamics of the material, leading to changes in its crystal structure and morphology (Najim et al., 2020). Similarly, doping can modify the surface properties of ZnO, including surface chemistry and reactivity. Dopants may introduce new surface states, altering the surface reactivity and overall properties (Wai & Li, 2022). Co-doping with multiple dopants can produce synergistic effects, enhancing the material's properties. Selecting the appropriate combination of dopants and optimizing their concentrations requires careful planning to achieve the desired characteristics for specific applications (Suriyachai et al., 2020). To assess the impact of doping on ZnO materials, several characterisation techniques, including X-ray diffraction, scanning electron microscopy, transmission electron microscopy, and spectroscopic approaches, are important. These approaches provide essential insights into the crystal structure, morphology, and the optical, electrical, and magnetic characteristics of the material (Shaikhaldein et al., 2021).

4. Window Layer of Solar Cells

The window layer in a solar cell denotes a transparent conducting layer usually positioned on the cell's front surface. The fundamental goal is to permit sunlight transmission while enabling the effective collection and

Cite this article as:
Ewansiha, K.O., Ewansiha,A.O., Ewansiha, C.E., & Ayo, S.A. (2025). Zinc Oxide co-doped with Aluminium and Boron (Al:B:ZnO) thin films via sol–gel process for solar cell window layers: A review. *FNAS Journal of Applied Chemical Science Research, 2*(3), 16-30.

extraction of electric charge carriers produced inside the cell (Battaglia et al., 2016). The window layer may serve as: The window layer often serves as an anti-reflective coating to reduce sunlight reflection. Minimising reflection allows for more sunlight penetration into the active layers of the solar cell, hence enhancing the cell's total efficiency (Steenhusen et al., 2023). The window layer serves as a transparent conducting layer in some solar cell designs. It permits the transmission of light while offering electrical conductivity to harness the produced power. Indium tin oxide (ITO) and zinc oxide (ZnO) are often used materials for this application. Passivation: The window layer may enhance the passivation of the solar cell surface. Passivation entails minimising surface imperfections and inhibiting carrier recombination, hence enhancing the overall efficiency of the solar cell. The window layer serves as a protective barrier, preventing moisture and pollutants from penetrating the underlying layers of the solar cell. This contributes to the sustained stability and efficacy of the cell (Chowdhury et al., 2023). The selection of window layer material for thin-film solar cells is contingent upon several aspects, including the exact thin-film technique used and the intended performance goals. Diverse materials have distinct advantages and compromises. The following are frequently used window layer materials for thin-film solar cells along with their attributes: Transparent conductive oxides, such as indium tin oxide (ITO) or fluorine-doped tin oxide (FTO), are extensively used as window layers in thin-film solar cells. They provide excellent electrical conductivity and transparency to facilitate light transmission. The total cost of ownership (TCO) may be substantial, and the accessibility of indium, an essential element of indium tin oxide (ITO), may be a worry (Chavan et al., 2023). Transparent Conductive Polymers (TCPs), such as poly(3,4-ethylenedioxythiophene): poly(styrenesulfonate) (PEDOT:PSS), are organic substances characterised by elevated transparency and commendable electrical conductivity. They exhibit flexibility and compatibility with roll-to-roll production techniques. TCPs may be beneficial for flexible thin-film solar cells. Their long-term stability and moisture resistance may be a challenge (Sharma et al., 2021). Metal Oxides, such as ZnO or titanium dioxide (TiO_2), are used as window layers in thin-film solar cells. Metal oxides can provide good electron transport properties and have the potential for low-cost production. Achieving high transparency while maintaining good conductivity can be a challenge with metal oxides (Salau et al., 2022). Perovskite solar cells are an emerging technology that has gained attention due to their high efficiency potential. Perovskite thin-film solar cells often incorporate a window layer made of materials like tin oxide (SnO_2) or titanium dioxide (TiO_2). These materials help with charge extraction and passivation of the perovskite layer. Perovskite solar cells are still under active research, and their commercial viability is being explored (Huang et al., 2021).

5. Synthesis of Zinc Oxide Nanoparticles

A variety of synthesis procedures for ZnO nanoparticles (ZnO-NPs) have been established, with the selection of method being contingent upon the desired application (Asif et al., 2023). ZnO nanoparticles have been synthesised in various sizes with techniques including solvothermal and hydrothermal synthesis, precipitation, polymerisation, laser ablation, sonochemical synthesis, chemical vapour deposition, thermal breakdown, and the sol-gel method. ZnO thin films are produced using methods such as atomic layer deposition (ALD), chemical vapour deposition (CVD), pulsed laser deposition (PLD), RF magnetron sputtering, epitaxial growth, self-assembly, co-precipitation, electrodeposition, spray pyrolysis, and sol-gel techniques. Precise control over size, morphology, and crystal structure during synthesis is necessary for applications in nanotechnology, such as in thin-film solar cells (Imran et al., 2021). Numerous synthesis methods are available today, enabling the production of ZnO-based materials tailored for specific applications (Owens et al., 2016). Among these, wet chemical methods, including sol-gel and hydrothermal techniques, stand out for their widespread use and effectiveness in producing high-quality doped ZnO nanoparticles. These methods offer a broad range of precursors and tunable parameters, allowing for significant customization of material properties. In contrast, combustion methods are valued for their speed, but they typically result in lower incorporation of dopant atoms into the ZnO lattice, making them less suitable for applications requiring high material quality (Carofiglio et al., 2020). Several established techniques are employed for depositing metal oxide films, with the method selected based on the desired film characteristics, the type of metal oxide, and production scale. In Chemical Vapour Deposition (CVD), volatile metal precursors are injected into a chamber, where they react and deposit as a thin layer on a substrate. This technique enables exact control of both composition and thickness. Variants of chemical vapour deposition (CVD) include atmospheric pressure chemical vapour deposition (APCVD), low-pressure chemical vapour deposition (LPCVD), and plasma-enhanced chemical vapour deposition (PECVD) (Vallejos et al., 2016). Sputtering and evaporation are two common Physical Vapour Deposition (PVD) processes. In evaporation, the source material is heated to produce a vapour that condenses into a film, whereas in sputtering, a target substance is bombarded with strong ions to dislodge atoms that then deposit onto a substrate. Film thickness and homogeneity can be effectively controlled with these methods (Savale, 2016). Sequential, self-limiting surface reactions are the foundation of ALD, which is renowned for its atomic-level accuracy. Because ALD deposits single atomic layers with

Cite this article as:
Ewansiha, K.O., Ewansiha,A.O., Ewansiha, C.E., & Ayo, S.A. (2025). Zinc Oxide co-doped with Aluminium and Boron (Al:B:ZnO) thin films via sol–gel process for solar cell window layers: A review. *FNAS Journal of Applied Chemical Science Research, 2*(3), 16-30.

remarkable regularity by introducing alternating pulses of precursor gases, it is perfect for ultra-thin metal oxide coatings (Im et al., 2012). Spray pyrolysis is an efficient method in which a precursor solution is atomised onto a heated substrate, resulting in decomposition that produces a metal oxide coating. This method is valued for its simplicity, cost-effectiveness, and suitability for large-area applications. Key parameters like precursor concentration, spray conditions, and substrate temperature must be optimized to achieve the desired film quality (Falcony et al., 2018).

6. Sol-Gel Synthesis of Zinc Oxide Nanoparticles

The sol-gel process entails the transformation of a precursor solution (sol) into a solid metal oxide layer (gel) via hydrolysis and condensation reactions as shown in figure 3. It provides versatility in film formulation and is compatible with diverse metal oxide compounds. Sol-gel deposition may be executed using spin coating, dip coating, or other methods. It facilitates low-temperature processing and is appropriate for many substrates (Bokov et al., 2021). The sol-gel process is used in the production of membranes, chemical sensors, optical gain media, electrochemical devices, photochromic and non-linear applications, as well as nanomaterials (Mahmood & Naeem, 2017). The sol-gel approach has garnered significant attention from researchers because to its ability to provide controlled consolidation, shape modification, nanostructure patterning, and low processing temperatures (Fardood et al., 2017). The procedure involves condensation, hydrolysis, and thermal breakdown of metal alkoxides or other metal-based precursors in a liquid environment. This results in the creation of a stable solution, referred to as a sol. As hydrolysis and condensation advance, viscosity escalates, leading to gel formation. Factors such as precursor concentration, temperature, and pH can be adjusted to influence the particle size. A crucial maturation stage follows, which may take several days, allowing for solvent removal, phase transitions, and Ostwald ripening. During this period, unstable compounds are eliminated to yield nanoparticles (Li et al., 2019). The sol-gel technique, categorised as a wet chemical approach, is extensively used for the synthesis of diverse nanostructures, especially metal oxide nanoparticles. It is considered economical and facilitates accurate regulation of chemical composition because to its low reaction temperature. The process starts with the creation of a homogenous sol from precursor ingredients, then transforming into a gel. The subsequent elimination of the solvent and the drying of the gel result in the final product. The drying technique substantially influences the properties of the resultant material (Dervin & Pillai, 2017; Bokov et al., 2021). This method offers numerous advantages for producing thin or thick films:

(i) It is simpler and more economical compared to other methods.

(ii) It enables easy coating on large or irregularly shaped substrates.

(iii) It requires minimal initial investment and low operating costs.

(iv) It does not interfere with pre-existing device structures during film deposition.

(v) It allows precise control of film thickness and porosity.

(vi) It supports the production of ultrafine films.

(vii) It operates at low temperatures.

(viii) It results in high surface areas in both film and powder forms, improving sensing capabilities (Periyasamy et al., 2020).

(ix) It allows for easy doping and modification of the composition to improve sensitivity and selectivity toward target gases (Esposito, 2019).

(x) The process is scalable.

(xi) It is ideal for producing thin-film sensors due to low processing costs and good control over film structure.

(xii) It is well-suited for fabricating sensitive layers in Metal Oxide Semiconductor (MOS) gas sensors.

(xiii) Thin films can be easily applied using spin- or dip-coating techniques.

(xiv) The resulting films are porous and composed of nanosized particles, unlike compact films from PVD or sputtering, which are less sensitive to gases (Mahmood & Naeem, 2017).

(xv) Spin-coated films can be patterned onto silicon sensor structures and are compatible with micro-fabrication processes.

Cite this article as:
Ewansiha, K.O., Ewansiha,A.O., Ewansiha, C.E., & Ayo, S.A. (2025). Zinc Oxide co-doped with Aluminium and Boron (Al:B:ZnO) thin films via sol–gel process for solar cell window layers: A review. *FNAS Journal of Applied Chemical Science Research, 2*(3), 16-30.

(xvi) Particle size can be finely tuned by controlling calcination temperature, yielding films with excellent porosity and surface-to-volume ratio, key to detecting reducing gases effectively.

(xvii) Unlike high-energy techniques like RF sputtering or vacuum evaporation that produce less stable films, sol-gel methods provide more stable coatings on substrates like alumina or silica glass via spin- or dip-coating (Adjimi et al., 2018). The doping process leads to various modifications in structural, optical, magnetic, and electrical properties. Through metal oxide doping, characteristics such as transmittance, refractive index, optical band gap, and electrical conductivity can be effectively adjusted. The optical band gap of boron-doped ZnO (B:ZnO) films diminishes progressively with increasing boron content. The carrier concentration in B:ZnO is inferior than that in Al:ZnO. Nonetheless, B:ZnO has superior semiconductor properties owing to a decrease in wurtzite crystallite dimensions and a reduced band gap (Eg), which enhances photocatalytic efficacy (Tahar & Tahar, 2005). All B:ZnO films have an average transmittance of over 90% within the visible light spectrum and possess an energy gap of 3.3 eV. The peak carrier concentration, mobility, and minimal resistivity were recorded at a boron doping level of 0.5% molar fraction, signifying this as the saturation threshold for boron in ZnO films. Aluminium is sometimes used as a dopant to augment the quantity of charge carriers, therefore decreasing resistance. Al:ZnO has garnered significant attention owing to its low resistance and high transmittance, making it especially appropriate for use as the window layer in solar cells. Moreover, Al:ZnO comprises non-toxic, plentiful components and can be synthesised at low temperatures, rendering it advantageous for economical, large-scale coating applications (Sharmin et al., 2019). Annealing tests indicate that a temperature of 350 °C for one hour is the minimum need to produce high-quality films. ZnO films with elevated concentrations exhibit more prominent diffraction peaks, whereas Al:ZnO reveals enhanced diffraction patterns and a significant blue shift of the absorption edge with increasing sol-gel concentration (Speaks, 2020). Thin films of Al-doped ZnO prepared using the affordable sol–gel dip-coating method show promise for applications in solar cell technologies (Bouacheria et al., 2022).

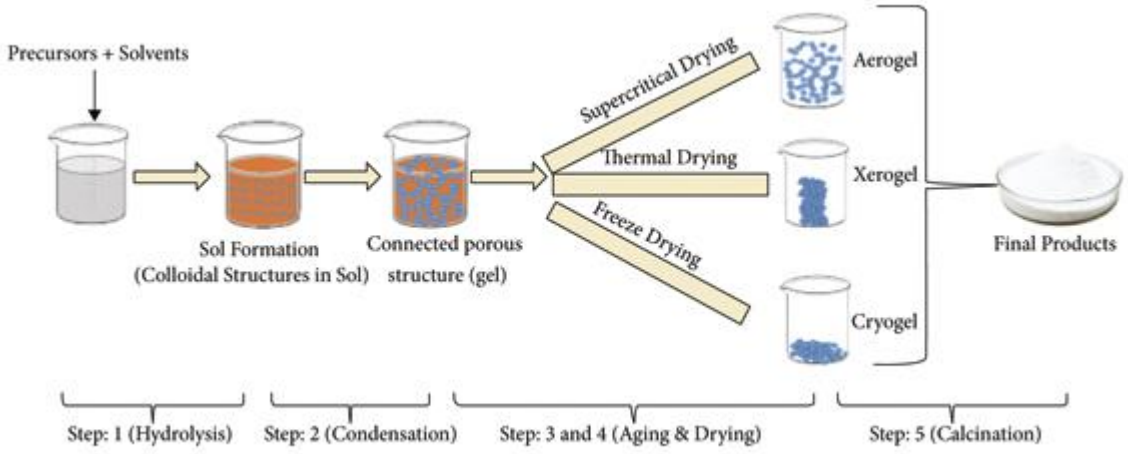


Figure 3: Schematic illustrating the many steps of the sol-gel process: from precursor to aerogel (Owens et al., 2016)

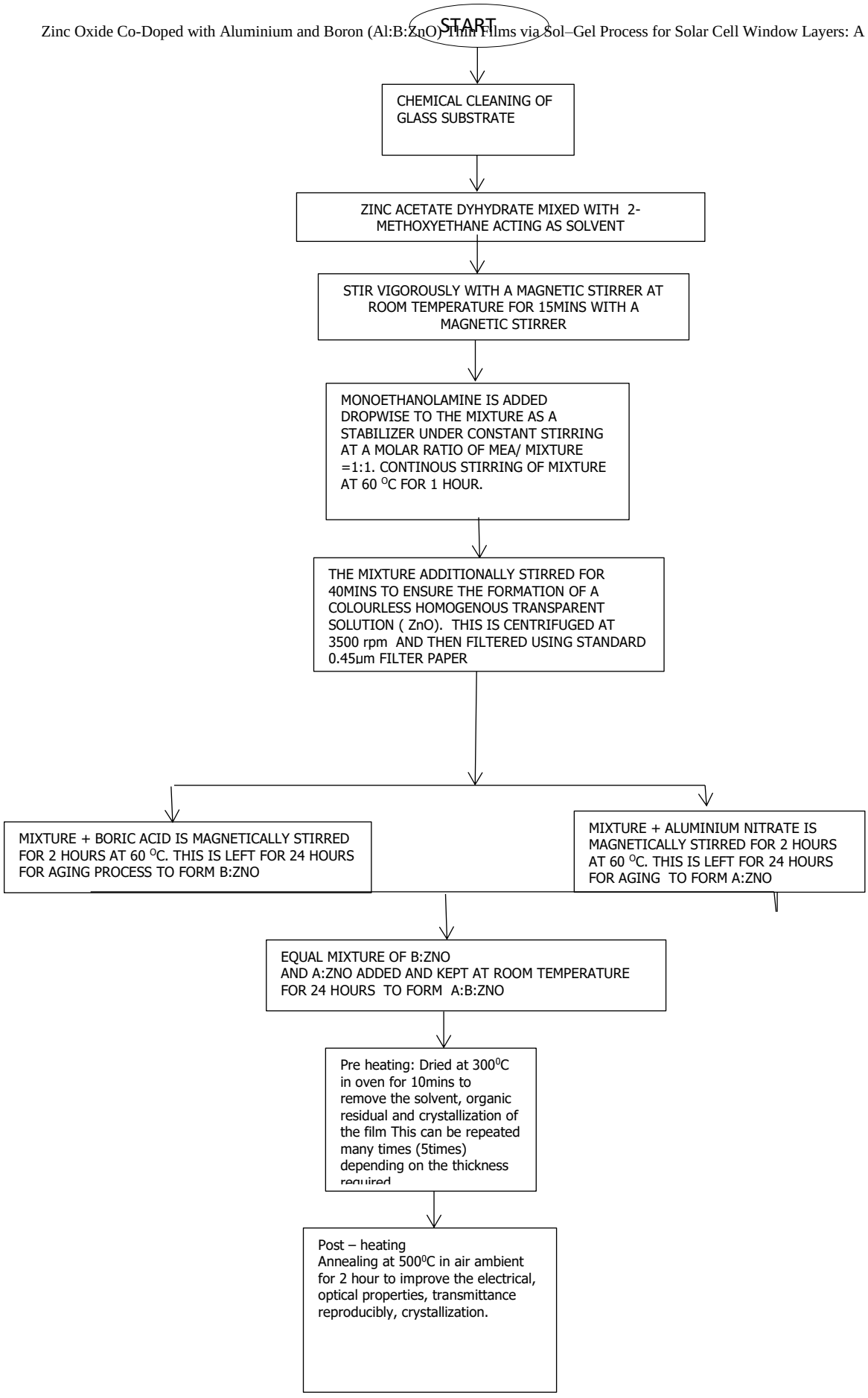
7. Doping of ZnO Nanoparticles

Zinc oxide (ZnO) has been one of the most promising TCO materials in recent years due to its strong chemical and mechanical endurance, exceptional optical and electrical qualities, and natural availability. Compared to the most widely used TCO materials (ITO, SnO2), this reduces the material's cost. Since undoped ZnO thin films are prone to instability, particularly at high temperatures, stability is a key benefit of doping ZnO. Conversely, doping increases the conductivity of ZnO thin films. ZnO is doped by substituting higher valence atoms from metals like indium, gallium, and aluminum for Zn^{2+} atoms. The effectiveness is determined by the ionic radius difference of zinc and the electronegativity of the dopant element. ZnO films show significantly improved conductivity and transparency when IIIA, IIIB, IVA, and IVB cations or non-metal anions are added. Y, Ti, Zr, Si, Sn, F, B, Al, Ga, and In have all been utilized in the doping process. Using the co-incorporating technique is one of the most efficient ways to improve the electrical conductivity and possible use of pure-ZnO films in PV applications. ZnO sample resistivity decreases greater with both types of co-doping than with single-cation doping. Up till now, Al

Cite this article as:
Ewansiha, K.O., Ewansiha,A.O., Ewansiha, C.E., & Ayo, S.A. (2025). Zinc Oxide co-doped with Aluminium and Boron (Al:B:ZnO) thin films via sol–gel process for solar cell window layers: A review. *FNAS Journal of Applied Chemical Science Research, 2*(3), 16-30.

has often been the main doping element in the co-doping procedure to create co-incorporated ZnO films with the following properties: B–Al, In–Al, Ga–Al, Sn–Al, Sc–Al, Ti–Al, V–Al, Mg–Al, Ni–Al, and Ag–Al (Gultepe & Atay, 2022). . Among these, aluminum (Al), gallium (Ga), and magnesium (Mg) doped ZnO TCO layers are a subject of ongoing research. The resistivity ($1.23x10^4$) and mobility (30.4 $cm^2/V.s$) of ZnO thin films are changed in opposite directions by Ga doping, according to the literature. In a similar manner, Al doping increases transmittance and decreases resistance by occupying Zinc (Zn) sites and producing more carriers. (Alkallas et al., 2022). Compared to merely the Al-incorporating procedure, the optical, surface, and electrical properties of ZnO film have been greatly enhanced by the Al-B co-doping approach, making it extremely appropriate for TCO applications. A sol- gel method is shown in figure 4 giving a flow chart of the complete doping process of Al and B co-doped with ZnO. After receiving Al-B co-doping treatment, the resistivity of ZnO film dropped from 6.12×10^2 Ωcm to 2.07×10^{-4} Ωcm. Furthermore, the ZnO film's transmittance values, surface homogeneity, and figure of merit value significantly increased due to the presence of Al and B components. Every investigation shown that the advantageous physical features of Al–B co-incorporated ZnO films make them a viable substitute for ITO films in TCO applications (Gultepe & Atay, 2022). Depending on the type of dopant and intended use, different doping concentrations have different effects on ZnO material properties. The following are a few ways that doping concentration affects ZnO properties: The electrical conductivity of ZnO materials can be strongly influenced by doping concentration and electrical conductivity. The introduction of charge carriers connected to the dopant may cause an increase in conductivity at low doping concentrations. However, the creation of dopant-related defects and the dispersion of charge carriers may cause the conductivity to decrease at greater doping concentrations (Raship et al., 2023). Doping concentration can also affect the emission and absorption spectra of ZnO materials. At modest doping levels, the optical characteristics might not change significantly. At greater doping concentrations, however, the optical characteristics could be drastically altered due to the creation of dopant-related energy levels (Mishra et al., 2022). Doping has an impact on ZnO materials' thermal stability as well, which is crucial for use in high-temperature settings. The thermal stability of ZnO materials might remain largely unaltered at low doping doses. Higher doping concentrations, however, may cause the dopant atoms to add more lattice strain, which could lower the material's thermal stability (Bouacheria et al., 2022). The doping concentration can also have an impact on ZnO material's crystal structure and shape. Dopants can introduce lattice strain and change the development kinetics of ZnO materials, hence modifying their morphology and crystal structure. In addition to surface characteristics, doping may affect ZnO materials' surface chemistry and reactivity. The surface characteristics and reactivity of ZnO materials can be altered by dopants' extra surface states and surface chemistry (Wai & Li, 2022). Co-doping a material with more than one dopant can improve its characteristics and have synergistic effects. (Suriyachai et al. (2020) state that choosing the appropriate dopant mixture and maximizing their concentrations might be difficult and need thorough evaluation of the required qualities for a particular application. Appropriate characterization techniques, including as X-ray diffraction, transmission electron microscopy, scanning electron microscopy, and spectroscopic approaches, are needed to evaluate how dopants alter a material's properties. These techniques can provide information about the morphological, optical, electrical, magnetic, and crystal structure of the material (Shaikhaldein et al., 2021).

Cite this article as:
Ewansiha, K.O., Ewansiha,A.O., Ewansiha, C.E., & Ayo, S.A. (2025). Zinc Oxide co-doped with Aluminium and Boron (Al:B:ZnO) thin films via sol–gel process for solar cell window layers: A review. *FNAS Journal of Applied Chemical Science Research, 2*(3), 16-30.



Cite this article as:
Ewansiha, K.O., Ewansiha,A.O., Ewansiha, C.E., & Ayo, S.A. (2025). Zinc Oxide co-doped with Aluminium and Boron (Al:B:ZnO) thin films via sol–gel process for solar cell window layers: A review. *FNAS Journal of Applied Chemical Science Research, 2*(3), 16-30.

Figure 4**:** Flow diagram of the synthesis and doping process of Sol-gel method

Conclusion

Thanks to their low cost, lightweight nature, and flexibility, transparent conductive oxides (TCOs) have become increasingly important for a wide range of optoelectronic applications such as photodetectors, light-emitting diodes (LEDs), and solar cells. A detailed overview of the characteristics, synthesis methods, and technological uses of ZnO is provided. ZnO-based transparent conductive oxides are often used as the window layer in thin-film photovoltaic cells. For these applications, TCOs must have great transparency in the visible and near-infrared parts of the electromagnetic spectrum, as well as superior electrical conductivity. Optical spectroscopy results show that ZnO films doped with boron (ZnO:B) maintain over 90% transparency in the visible range, which slightly declines in the near-infrared range. The best performance in terms of carrier concentration, conductivity, and mobility was achieved at a deposition temperature of 300 °C, attributed to enhanced crystallinity (Mwakyusa et al., 2022). Thin films of aluminum-doped ZnO (AZO) have attracted significant attention due to their strong electrical performance. AZO thin films are stable, affordable, and show promise as alternatives for transparent conductive layers in solar cells and display technologies (Znaidi et al., 2013). AZO films have demonstrated resistivities as low as 0.85×10^{-2} Ω·cm and 0.51×10^{-4} Ω·cm (Gao & Banerjee, 2014). When both aluminum and boron are incorporated, ZnO films display notable improvements in transmittance, surface uniformity, and figure of merit. These co-doped films show physical properties that position them as viable alternatives to indium tin oxide (ITO) in TCO applications (Gultepe & Atay, 2022).

Recommendations

(Add recommendations)

References

Adjimi, A., Zeggar, M. L., Attaf, N., & Aida, M. S. (2018). Fluorine-doped tin oxide thin films deposition by sol-gel technique. *Journal of Crystallization Process and Technology*, *08*(04), 89–106. https://doi.org/10.4236/jcpt.2018.84006

Alkallas, F. H., Trabelsi, A. B. G., Nasser, R., Fernandez, S., Song, J. M., & Elhouichet, H. (2022). Promising Cr-Doped ZnO Nanorods for Photocatalytic Degradation Facing Pollution. *Applied Sciences (Switzerland)*, *12*(1). https://doi.org/10.3390/app12010034

Akhta, M. S., Riaz, S., Noor, R., & Naseem, S. (2013). Optical and structural properties of ZnO thin films for solar cell applications. Advanced Science Letters, 19(3), 834–838. https://doi.org/10.1166/asl.2013.4822

Alsaad, A. M., Ahmad, A. A., Qattan, I. A., Al-Bataineh, Q. M., & Albataineh, Z. (2020). Structural, optoelectrical, linear, and nonlinear optical characterizations of dip-synthesized undoped zno and group iii elements (B, al, ga, and in)-doped zno thin films. *Crystals*, *10*(4). https://doi.org/10.3390/cryst10040252

Alsagri, A. S. (2022). Photovoltaic and Photovoltaic Thermal Technologies for Refrigeration Purposes: An Overview. *Arabian Journal for Science and Engineering*, *47*(7), 7911–7944. https://doi.org/10.1007/s13369-021-06534-2

Amakali, T., Daniel, L. S., Uahengo, V., Dzade, N. Y., & Leeuw, N. H. De. (2020). Structural and Optical Properties of ZnO Thin Films Sol – Gel Methods. *Crystals*, *10*(2), 132.

Andjela B, S. (2021). Application of photovoltaic technology in the use of solar energy. *Annals of Environmental Science and Toxicology*, *5*, 094–098. https://doi.org/10.17352/aest.000044

Asif, N., Amir, M., & Fatma, T. (2023). Recent advances in the synthesis, characterization and biomedical applications of zinc oxide nanoparticles. *Bioprocess and Biosystems Engineering*, 0123456789. https://doi.org/10.1007/s00449-023-02886-1

Battaglia, C., Cuevas, A., & De Wolf, S. (2016). High-efficiency crystalline silicon solar cells: Status and perspectives. *Energy and Environmental Science*, *9*(5), 1552–1576. https://doi.org/10.1039/c5ee03380b

Bhandari, K. P., Sapkota, D. R., Jamarkattel, M. K., Stillion, Q., & Collins, R. W. (2023). Zinc Oxide Nanoparticles—Solution-Based Synthesis and Characterizations. *Nanomaterials*, *13*(11), 1–15. https://doi.org/10.3390/nano13111795

Bin Rafiq, M. K. S., Amin, N., Alharbi, H. F., Luqman, M., Ayob, A., Alharthi, Y. S., Alharthi, N. H., Bais, B., & Akhtaruzzaman, M. (2020). WS2: A New Window Layer Material for Solar Cell Application. *Scientific Reports*, *10*(1), 1–11. https://doi.org/10.1038/s41598-020-57596-5

Bokov, D., Turki Jalil, A., Chupradit, S., Suksatan, W., Javed Ansari, M., Shewael, I. H., Valiev, G. H., & Kianfar, E. (2021). Nanomaterial by Sol-Gel method: Synthesis and application. *Advances in Materials Science*

and Engineering. https://doi.org/10.1155/2021/5102014

Bouacheria, M. A., Djelloul, A., Adnane, M., Larbah, Y., & Benharrat, L. (2022). Characteristics of ZnO and Al doped zno thin films prepared by sol gel method for solar cell applications. *Journal of Inorganic and Organometallic Polymers and Materials*, *32*(7), 2737–2747. https://doi.org/10.1007/s10904-022-02313-0

Carofiglio, M., Barui, S., Cauda, V., & Laurenti, M. (2020). Doped zinc oxide nanoparticles: Synthesis, characterization and potential use in nanomedicine. *Applied Sciences (Switzerland)*, *10*(15). https://doi.org/10.3390/app10155194

Castañeda, L. (2022). Review of Con-ducting Oxides Semiconductors in Thin Solid Films. *Biomed J Sci & Tech Res*, *41*(1), 32261–32270. https://doi.org/10.26717/BJSTR.2022.41.006531

Chavan, G. T., Kim, Y., Khokhar, M. Q., Hussain, S. Q., Cho, E. C., Yi, J., Ahmad, Z., Rosaiah, P., & Jeon, C. W. (2023). A Brief Review of Transparent Conducting Oxides (TCO): The Influence of Different Deposition Techniques on the Efficiency of Solar Cells. *Nanomaterials*, *13*(7). https://doi.org/10.3390/nano13071226

Chowdhury, T. A., Bin Zafar, M. A., Sajjad-Ul Islam, M., Shahinuzzaman, M., Islam, M. A., & Khandaker, M. U. (2023). Stability of perovskite solar cells: issues and prospects. *RSC Advances*, *13*(3), 1787–1810. https://doi.org/10.1039/d2ra05903g

Dervin, S., & Pillai, S. C. (2017). An introduction to sol-gel processing for aerogels. February, 1–22. https://doi.org/10.1007/978-3-319-50144-4_1

Doroody, C., Rahman, K. S., Kiong, T. S., & Amin, N. (2022). Optoelectrical impact of alternative window layer composition in CdTe thin film solar cells performance. *Solar Energy*, *233*(February), 523–530. https://doi.org/10.1016/j.solener.2022.01.049

Esposito, S. (2019). Traditional sol-gel chemistry as a powerful tool for the preparation of supported metal and metal oxide catalysts. *Materials*, *12*(4), 1–25. https://doi.org/10.3390/ma12040668

Gultepe, O., & Atay, F. (2022). Al and B co-doped ZnO samples as an alternative to ITO for transparent electronics applications. *Journal of Materials Science: Materials in Electronics*, *33*(18), 15039–15053. https://doi.org/10.1007/s10854-022-08421-4

Hassan, H. Z., & Mohamad, A. A. (2012). A review on solar cold production through absorption technology. *Renewable and Sustainable Energy Reviews*, *16*(7), 5331–5348. https://doi.org/10.1016/j.rser.2012.04.049

Holechek, J. L., Geli, H. M. E., Sawalhah, M. N., & Valdez, R. (2022). A Global Assessment: Can Renewable Energy Replace Fossil Fuels by 2050? *Sustainability (Switzerland)*, *14*(8), 1–22. https://doi.org/10.3390/su14084792

Huang, G., Wang, K., & Markides, C. N. (2021). *Photovoltaic / Thermal Solar Collectors* (Issue January). https://doi.org/10.1016/B978-0-12-819727-1.00051-0

Huang, H. H., Liu, Q. H., Tsai, H., Shrestha, S., Su, L. Y., Chen, P. T., Chen, Y. T., Yang, T. A., Lu, H., Chuang, C. H., Lin, K. F., Rwei, S. P., Nie, W., & Wang, L. (2021). A simple one-step method with wide processing window for high-quality perovskite mini-module fabrication. *Joule*, *5*(4), 958–974. https://doi.org/10.1016/j.joule.2021.02.012

Im, H., Wittenberg, N. J., Lindquist, N. C., & Oh, S. H. (2012). Atomic layer deposition: A versatile technique for plasmonics and nanobiotechnology. *Journal of Materials Research*, *27*(4), 663–671. https://doi.org/10.1557/jmr.2011.434

Imran, H. J., Hubeatir, K. A., Aadim, K. A., & Abd, D. S. (2021). Preparation methods and classification study of nanomaterial: A review. *Journal of Physics: Conference Series*, *1818*(1). https://doi.org/10.1088/1742-6596/1818/1/012127

Jang, S., Karade, V. C., Jang, J. S., Jo, E., Shim, H., Kim, S. G., Patil, K., Gour, K. S., & Kim, J. H. (2023). Achieving over 10% device efficiency in Cu2ZnSn(S,Se)4 thin-film solar cells with modifications of window layer properties. *Journal of Alloys and Compounds*, *930*, 167302. https://doi.org/10.1016/j.jallcom.2022.167302

Khantoul, A. R., Sebais, M., Rahal, B., Boudine, B., & Halimi, O. (2018). Structural and optical properties of zno and co doped ZnO thin films prepared by sol-gel. *Acta Physica Polonica A*, *133*(1), 114–117. https://doi.org/10.12693/APhysPolA.133.114

Koralli, P., Varol, S. F., Mousdis, G., Mouzakis, D. E., Merdan, Z., & Kompitsas, M. (2022). Comparative Studies of Undoped/Al-Doped/In-Doped ZnO Transparent Conducting Oxide Thin Films in Optoelectronic Applications. *Chemosensors*, *10*(5). https://doi.org/10.3390/chemosensors10050162

Larsson, F. (2020). Window Layer Structures for Chalcopyrite Thin-Film Solar Cells. http://uu.diva-portal.org/smash/record.jsf?pid=diva2%3A1456222&dswid=-5593

Li, Y., Cheng, M., Jungstedt, E., Xu, B., Sun, L., & Berglund, L. (2019). Optically Transparent Wood Substrate for Perovskite Solar Cells. *ACS Sustainable Chemistry and Engineering*, *7*(6), 6061–6067.

https://doi.org/10.1021/acssuschemeng.8b06248

Mahmood, A., & Naeem, A. (2017). Sol-gel-derived doped zno thin films: Processing, properties, and applications. *Recent Applications in Sol-Gel Synthesis.* https://doi.org/10.5772/67857

Mandal, A. K., Katuwal, S., Tettey, F., Gupta, A., Bhattarai, S., Jaisi, S., Bhandari, D. P., Shah, A. K., Bhattarai, N., & Parajuli, N. (2022). Current research on zinc oxide nanoparticles: Synthesis, characterization, and biomedical applications. *Nanomaterials*, *12*(17). https://doi.org/10.3390/nano12173066

Mishra, P. N., Mishra, P. K., & Pathak, D. (2022). The influence of Al doping on the optical characteristics of ZnO nanopowders obtained by the low-cost sol-gel method. *Chemistry (Switzerland)*, *4*(4), 1136–1146. https://doi.org/10.3390/chemistry4040077b

Naser, A., Hachim, D., & Abed, Q. (2022). *A review of Effect the Zinc Oxide deposition on Crystalline Silicon Solar Cells.* https://doi.org/10.4108/eai.7-9-2021.2314810

Negrescu, A. M., Killian, M. S., Raghu, S. N. V., Schmuki, P., Mazare, A., & Cimpean, A. (2022). Metal oxide nanoparticles: Review of Synthesis, Characterization and Biological Effects. *Journal of Functional Biomaterials*, *13*(4). https://doi.org/10.3390/jfb13040274

Neha, & Rambeer, J. (2021). Renewable energy sources: A review. *Journal of Physics: Conference Series*, *1979*(1). https://doi.org/10.1088/1742-6596/1979/1/012023

Nourdine, A., Abdelli, M., Charvin, N., & Flandin, L. (2021). Custom synthesis of zno nanowires for efficient ambient air-processed solar cells. *ACS Omega*, *6*(48), 32365–32378. https://doi.org/10.1021/acsomega.1c01654

Oleshko, O., Husak, Y., Korniienko, V., Pshenychnyi, R., Varava, Y., Kalinkevich, O., Pisarek, M., Grundsteins, K., Pogorielova, O., Mishchenko, O., Simka, W., Viter, R., & Pogorielov, M. (2020). Biocompatibility and antibacterial properties of zno-incorporated anodic oxide coatings on TiZrNb alloy. *Nanomaterials*, *10*(12), 1–15. https://doi.org/10.3390/nano10122401

Orori, M. C. (2023). Properties of Zinc Oxide thin layers for Photovoltaic Applications. (Indicate the journal), 7(3), 1–9. https://doi.org/10.19080/JOJMS.2023.07.555716

Owens, G. J., Singh, R. K., Foroutan, F., Alqaysi, M., Han, C. M., Mahapatra, C., Kim, H. W., & Knowles, J. C. (2016). Sol-gel based materials for biomedical applications. *Progress in Materials Science*, *77*, 1–79. https://doi.org/10.1016/j.pmatsci.2015.12.001

Pastuszak, J., & Węgierek, P. (2022). Photovoltaic cell generations and current research directions for their development. *Materials*, *15*(16). https://doi.org/10.3390/ma15165542

Periyasamy, A. P., Venkataraman, M., Kremenakova, D., Militky, J., & Zhou, Y. (2020). Progress in sol-gel technology for the coatings of fabrics. *Materials*, *13*(8). https://doi.org/10.3390/MA13081838

Prasetyo, S. D., Prabowo, A. R., & Arifin, Z. (2023). The use of a hybrid photovoltaic/thermal (PV/T) collector system as a sustainable energy-harvest instrument in urban technology. *Heliyon*, *9*(2), e13390. https://doi.org/10.1016/j.heliyon.2023.e13390

Regmi, G., Rijal, S., & Velumani, S. (2023). Aluminum-doped zinc oxide (AZO) ultra-thin films deposited by radio frequency sputtering for flexible Cu (In, Ga) Se 2 solar cells. *Memories - Materials, Devices, Circuits and Systems*, *5*(June), 100064. https://doi.org/10.1016/j.memori.2023.100064

Sarma, B., Barman, D., & Sarma, B. K. (2019). AZO (Al:ZnO) thin films with high figure of merit as stable indium free transparent conducting oxide. *Applied Surface Science*, #pagerange#. https://doi.org/10.1016/j.apsusc.2019.02.146

Savale, P. A. (2016). Physical vapor deposition (PVD) methods for synthesis of thin films: A comparative study. *Scholars Research Library Archives of Applied Science Research*, *8*(5), 1–8. http://scholarsresearchlibrary.com/archive.html

Shaikhaldein, H. O., Al-qurainy, F., Khan, S., Nadeem, M., Tarroum, M., Salih, A. M., Gaafar, A. Z., Alshameri, A., Alansi, S., Alenezi, N. A., & Alfarraj, N. S. (2021). Biosynthesis and characterization of zno nanoparticles using ochradenus arabicus and their effect on growth and antioxidant systems of maerua oblongifolia. *Plants*, *10*(1), 1801.

Sharma, S., Singh, K., Kumar, S., Bhatt, K., Dwivedi, Y., Rana, A., & Tripathi, C. C. (2021). Fabrication of reduced graphene oxide modified poly(3,4-ethylenedioxythiophene) polystyrene sulfonate based transparent conducting electrodes for flexible optoelectronic application. *SN Applied Sciences*, *3*(1), 1–8. https://doi.org/10.1007/s42452-020-04034-w

Sharmin, A., Tabassum, S., Bashar, M. S., & Mahmood, Z. H. (2019). Depositions and characterization of sol–gel processed Al-doped ZnO (AZO) as transparent conducting oxide (TCO) for solar cell application. *Journal of Theoretical and Applied Physics*, *13*(2), 123–132. https://doi.org/10.1007/s40094-019-0329-0

Shweta, K. P., & Thapa, K. B. (2019). Synthesis and characterization of ZnO nano-particles for solar cell application by the cost effective co-precipitation method without any surfactants. *AIP Conference Proceedings*, *2142(September)*. https://doi.org/10.1063/1.5122336

Sivaraj, S., Rathanasamy, R., Kaliyannan, G. V., Panchal, H., Jawad Alrubaie, A., Musa Jaber, M., Said, Z., & Memon, S. (2022). A Comprehensive Review on Current Performance, Challenges and Progress in Thin-Film Solar Cells. *Energies*, *15*(22). https://doi.org/10.3390/en15228688

Speaks, D. T. (2020). Effect of concentration, aging, and annealing on sol gel ZnO and Al-doped ZnO thin films. *International Journal of Mechanical and Materials Engineering*, *15*(1). https://doi.org/10.1186/s40712-019-0113-6

Steenhusen, S., Scherg, G. P., & Löbmann, P. (2023). Increased durability of sol–gel derived MgF2 antireflective coatings capped by vapor deposition. *Journal of Sol-Gel Science and Technology*, *105*(1), 58–62. https://doi.org/10.1007/s10971-022-05977-9

Suriyachai, N., Chuangchote, S., Laosiripojana, N., Champreda, V., & Sagawa, T. (2020). Synergistic effects of co-doping on photocatalytic activity of titanium dioxide on glucose conversion to value-added chemicals. *ACS Omega*, *5*(32), 20373–20381. https://doi.org/10.1021/acsomega.0c02334

Vallejos, S., Di Maggio, F., Shujah, T., & Blackman, C. (2016). Chemical vapour deposition of gas sensitive metal oxides. *Chemosensors*, *4*(1), 1–18. https://doi.org/10.3390/chemosensors4010004

Vignesh, K., Nair, A. S., Udhayakeerthana, C., & Kalaivani, T. (2022). Synthesis and characterization ZnO nanoparticles using sol-gel method and their antibacterial study. *IOP Conference Series: Materials Science and Engineering*, *1219*(1), 012019. https://doi.org/10.1088/1757-899x/1219/1/012019

Wai, H. S., & Li, C. (2022). Effect of aluminum doping ratios on the properties of aluminum-doped zinc oxide films deposited by mist chemical vapor deposition method applying for photocatalysis. *Nanomaterials*, *12*(2). https://doi.org/10.3390/nano12020195

Zyoud, S. H., Zyoud, A. H., Abdelkader, A., & Ahmed, N. M. (2021). Numerical simulation for optimization of znte-based thin-film heterojunction solar cells with different metal chalcogenide buffer layers replacements: Scaps-1d simulation program. *International Review on Modelling and Simulations*, *14*(2), 79–88. https://doi.org/10.15866/iremos.v14i2.19954