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Review

Thin-Film Deposition for ZnO-Based Semiconductors: Advantages, Challenges, and Future Directions

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Abstract: This research dives into the field of thin film deposition, with a particular emphasis on its application in ZnO-based semiconductors. The examination tries to illustrate the array of benefits, intricate challenges, and bright prospects inherent in this field through an in-depth case study. Notably, the work emphasizes the benefits of thin film deposition techniques in ZnO-based semiconductor production, such as precise control over film thickness, improved material use, and the ability to modify electrical properties. It does, how-ever, recognize the difficulties in assuring uniformity and quality control in deposition, dealing with complex deposition processes, addressing interface effects to maximize device performance, and navigating material compatibility constraints. In terms of the future, the study sees significant potential in the development of advanced materials to augment ZnO-based semiconductor functionalities, the incorporation of nanotechnology to boost performance, and the emergence of novel monitoring strategies for real-time quality assurance during deposition. Sustainable deposition methods are also being considered considering environmental concerns. The study continues by emphasizing the revolutionary significance of ZnO-based semiconductors in many applications and emphasizing the importance of interdisciplinary collaboration to unlock the full spectrum of benefits and overcome hurdles in this dynamic field. This research provides a comprehensive look at the complex domain of thin film deposition in ZnO-based semiconductor environments, shedding light on its potential to transform technological landscapes and inspire creative solutions.

Keywords: Thin Film Deposition; ZnO; Techniques; Challenges; Prospects.

1. Introduction

Thin-film deposition plays an essential role in the fabrication of semiconductor materials, especially those based on zinc oxide (ZnO), a wide-bandgap semiconductor recognized for its optical transparency, high electron mobility, and chemical stability [1]. These characteristics position ZnO as a key material for applications in optoelectronics, transparent electronics, sensors, and emerging flexible devices. High-quality ZnO thin films are typically fabricated using chemical vapor deposition (CVD), physical vapor deposition (PVD), and atomic layer deposition (ALD). Among these, ALD has become the preferred choice due to its self-limiting surface reaction mechanism, which offers atomic-level thickness control, excel-lent conformality, and remarkable uniformity on 3D structures [2].

The continued demand for high-performance electronic and optoelectronic devices requires reliable fabrication of both p-type and n-type ZnO semiconducting layers. However, achieving stable p-type ZnO remains difficult because of intrinsic defect compensation, low dopant solubility, and dopant diffusion. For n-type ZnO, although deposition is more straightforward, optimizing carrier concentration, mobility, and defect control remains crucial [3]. These challenges highlight the need to deeply understand how ALD parameters—precursor chemistry, surface reactions, temperature, pressure, and post-treatments influence dopant incorporation and electrical behavior [4].

Despite extensive work on doped ZnO films, the literature lacks a unified and comparative review that:

1) Integrates ALD strategies for both p-type and n-type ZnO;

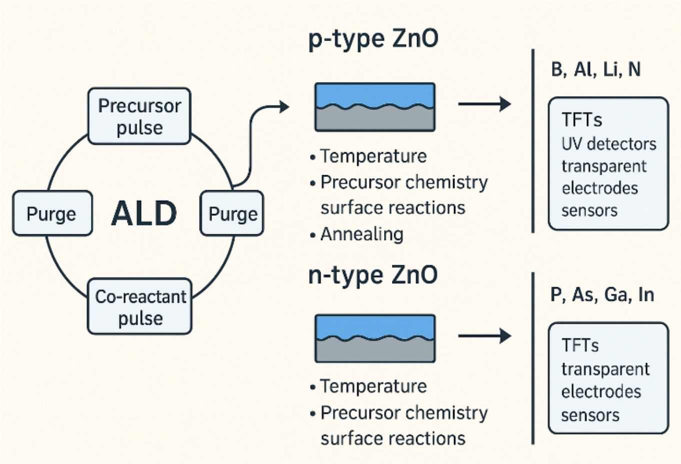

Figure 1. Schematic overview of ALD-grown doped ZnO thin films.

2) Explains dopant incorporation mechanisms and defect engineering during ALD;
3) Compares dopant systems (B, Al, Li for p-type; Ga, In, P, As for n-type);
4) Discusses process–property relationships linking ALD chemistry to electrical performance;
5) Highlights current bottlenecks and future research directions [5].

This gap underscores the importance of the present re-view. By consolidating recent advances in precursor chemistry, dopant activation, post-deposition annealing, interface passivation, and in-situ monitoring, this work provides a comprehensive overview of ALD-based approaches for tailoring ZnO conductivity [6]. The goal is to clarify how ALD can enable low-defect, highly controlled p-type and n-type films, thereby supporting progress in transparent electronics, UV optoelectronics, and next-generation semiconductor devices.

The illustration in figure 1 summarizes how Atomic Layer Deposition (ALD) enables precise control of ZnO doping pathways toward p-type and n-type conductivity. The ALD cycle comprising precursor pulse, purge, co-reactant pulse, and purge allows atomic-scale regulation of surface reactions and film composition [7]. By tuning growth temperature, precursor chemistry, and post-deposition annealing, ZnO can be engineered into p-type form using dopants such as B, Al, Li, and N, or into n-type form using P, As, Ga, and In. These controlled doping strategies support a wide range of applications including thin-film transistors (TFTs), UV photodetectors, transparent electrodes, and chemical sensors [8].

To guide the reader, the remainder of this paper is organized as follows. Section 2 provides a detailed review of the major thin-film deposition techniques used for ZnO-based semiconductors, highlighting their operating principles, advantages, and limitations. Section 3 summarizes the development of p-type and n-type ZnO films and discusses key material challenges such as dopant activation, defect compensation, and stability [6]. Section 4 examines the role of Atomic Layer Deposition (ALD) in fabricating semiconducting thin films, including typical process constraints and recent advancements. Section 5 presents a comparative evaluation of ALD with other deposition methods in terms of growth control, film quality, scalability, and suitability for device applications. Section 6 provides an integrated discussion on the implications of these findings for current and emerging technologies, followed by Section 7, which concludes the review by outlining remaining challenges and future research directions in ZnO-based semiconductor thin-film deposition.

2. Methodology

This review was conducted by systematically collecting, screening, and synthesizing published research on thin-film deposition methods for ZnO-based semiconductor materials. Relevant literature was identified through comprehensive searches of major scientific databases, including Scopus, Web of Science, IEEE Xplore, and ScienceDirect, using keywords such as "ZnO thin films," "deposition techniques," "sputtering," "sol–gel," "PLD," "ZnO doping," and "semiconductor thin films." The search covered publications from 2000 to 2025 to capture both foundational studies and recent advancements in processing technologies. After removing duplicates, titles and abstracts were screened to exclude articles unrelated to ZnO thin films, such as those focusing on bulk ceramics or non-semiconducting oxides [9]. Full-text screening was then carried out to select studies that specifically discussed deposition processes, material properties, process optimization strategies, challenges, and emerging research directions [10].

Eligible studies were categorized based on the deposition technique used—such as RF magnetron sputtering, sol–gel processing, pulsed laser deposition, chemical vapor deposition, and atomic layer deposition—and further organized according to themes including structural quality, surface morphology, dopant incorporation, electrical behavior, and device applications [11]. Data extraction focused on consistent parameters across studies, such as deposition conditions, film thickness, post-treatment processes, and measured optical or electrical properties. In cases where quantitative results varied significantly between studies, the differences were examined in terms of process parameters, equipment configuration, or material purity [12]. A narrative synthesis approach was used to compare advantages, limitations, and technological relevance of each deposition method, while special attention was given to identifying common trends such as mobility enhancement strategies, defect control techniques, and emerging challenges in scaling ZnO thin-film technologies. By integrating findings across multiple studies, this methodology ensures a comprehensive, unbiased, and technically grounded assessment of the current state and future directions of ZnO thin-film deposition [13].

3. Thin Films Deposition

Thin film deposition is the process of depositing a thin layer of material onto a substrate that typically ranges in thickness from a few nanometers to several micrometers. This approach is frequently utilized to build functional layers with specified qualities in a variety of industries, including electronics, optics, coatings, and material research [14]. Thin films have the potential to change the surface properties of substrates, improve their performance, and enable the development of new technologies. A thin-film deposition process called atomic layer deposition (ALD) is used in nanotechnology and material science to produce uniform, ultra-thin films with perfect control over thickness. Chemical vapor deposition (CVD) is a subset of ALD [15], which is based on the successive exposure of a substrate to different precursor gases. There are normally four steps in the ALD process:

1) Adsorption: A precursor gas is introduced to the substrate, and when it reacts chemically with the surface, an adsorbed species monolayer is created [16]. Only one layer of precursor molecules can connect to the surface due to the self-limiting nature of the adsorption, which guarantees a homogeneous and conformal coating.
2) Purge: After the initial precursor has been added, the reaction chamber is purge with an inert gas to get rid of any excess unreacted precursor and reaction byproducts.
3) Second precursor adsorption: The substrate is exposed to a second precursor gas, which reacts with the adsorbed species from the first step. This reaction results in the formation of a new layer on top of the initial monolayer.
4) Second purge: Similar to the first purge, the reaction chamber is purged again to remove any unreacted precursors or by-products.

The procedure is then repeated a predetermined number of times to precisely build up the required layer thickness. The composition and thickness of the thin film can be precisely customized by carefully selecting the precursor gases and managing the number of cycles. ALD is used in many different fields, such as barrier coatings, microelectronics, catalysis, energy storage, and semiconductor devices [17]. It is a crucial tool in the creation of cutting-edge nanoscale technologies due to its capacity to manufacture very homogeneous and conformal films with exact thickness control. To further increase its adaptability in industrial applications, ALD is compatible with a variety of substrates, including silicon, metals, glass, and polymers.

4. Techniques of Atomic Layer Deposition

P-type semiconducting thin films are deposited using atomic layer deposition (ALD), which adheres to the main principles of ALD but uses precursor chemistries and growth conditions that are appropriate for producing p-type materials [18]. The following are some typical methods and factors for ALD of p-type semiconducting thin films:

1) Precursor Selection: For the deposition of high-quality p-type semiconducting films, the right p-type precursors must be chosen. Organometallic compounds comprising elements like boron (B), aluminum (Al), and gallium (Ga) are frequently utilized as p-type precursors. Trimethylaluminum (TMA), trimethyl borane (TMB), and trimethylgallium (TMG) are a few examples [19].
2) Growth Temperature: In p-type ALD, the growth temperature is regulated to guarantee proper surface reactions and high-quality films. It should be chosen based on the p-type precursor utilized and the desired film qualities.
3) Controlling Carrier Concentration: The precursor dose and the number of ALD cycles can be changed to alter the carrier concentration in p-type semiconducting films. In order to get the appropriate electrical characteristics, the carrier concentration must be precisely controlled [20].
4) Passivating the substrate's surface before the ALD process is crucial for reducing surface flaws and ensuring optimal electrical performance. This process can enhance the video's quality and minimize undesirable interface conditions.
5) Doping is a crucial step in the production of p-type semiconductors. It entails adding substances (dopants) to the semiconductor lattice in order to change its electrical characteristics. For p-type doping, dopants like boron (B) are frequently utilized.
6) Due to its inherent self-limitation, ALD naturally provides high film uniformity and conformity [21]. To keep the substrate homogeneous, it is crucial to make sure the deposition process is tightly managed.
7) Surface Cleaning: To ensure that the p-type thin film will adhere well after the ALD process, the substrate surface should be properly cleaned to get rid of any impurities or native oxides.
8) In situ Monitoring: Real-time analysis of the ALD surface reactions and film growth can be done using in situ monitoring techniques like mass spectrometry or spectroscopic ellipsometry. This makes it possible to optimize the process and guarantees uniform film characteristics.

5. Techniques of Thin Films Deposition

The process of Atomic Layer Deposition (ALD) of n-type semiconducting thin films adheres to the same general principles as ALD but uses certain precursor chemistries and growth conditions that are appropriate for depositing n-type materials. For the ALD of n-type semiconducting thin films, some of the typical methods and factors are listed below:

1) Choice of Substrate: The p-type thin film's quality can be impacted by the substrate that is selected. In order to produce the desired film qualities, different substrates might need particular surface treatments or considerations [22].
2) Post-Deposition Annealing: To activate dopants, increase crystal quality, and improve the electrical performance of the p-type thin film, post-deposition annealing may occasionally be required [23].
3) Precursor Selection: For the deposition of high-quality n-type semiconducting films, the right n-type precursors must be chosen. Organometallic compounds comprising elements like phosphorus (P), arsenic (As), and antimony (Sb) are frequently utilized as n-type precursors [24]. Examples include trimethyl antimony (TMSb), phosphine (PH3), and arsine (AsH3).
4) Growth Temperature: To guarantee effective surface reactions and high-quality films, the growth temperature in n-type ALD is optimized. It should be chosen based on the n-type precursor utilized and the desired film qualities.
5) Controlling the Carrier Concentration: The precursor dosage and the number of ALD cycles can be changed to alter the carrier concentration in n-type semiconducting films. In order to get the appropriate electrical characteristics, the carrier concentration must be precisely controlled.
6) Passivating the substrate's surface before the ALD process is crucial for reducing surface flaws and ensuring optimal electrical performance. This process might raise the level of the film and lessen undesirable interface conditions.
7) Doping is a crucial process in the production of n-type semiconductors. It entails adding substances (dopants) to the semiconductor lattice in order to change its electrical characteristics. For n-type doping, dopants like phosphorous (P) or arsenic (As) are frequently employed.
8) Due to its inherent self-limitation, ALD naturally provides high film uniformity and conformality. To keep the substrate homogeneous, it is crucial to make sure the deposition process is tightly managed.
9) Surface Cleaning: To ensure that the n-type thin film will adhere well after the ALD process, the substrate surface should be carefully cleaned to get rid of any impurities or native oxides.
10) In situ Monitoring: Real-time analysis of the ALD surface reactions and film growth can be done using in situ monitoring techniques like mass spectrometry or spectroscopic ellipsometry. This makes it possible to optimize the process and guarantees uniform film characteristics.

6. Challenges of Thin Films Deposition

The case study on thin film deposition for ZnO-based semiconductors illuminates numerous important obstacles associated with this complex technique. The most difficult of these difficulties is achieving constant and uniform film deposition across complicated substrates. Because of ZnO's sensitivity to growing conditions and the complexities of surface interactions, the thickness distribution might be uneven, affecting the overall quality and performance of the semiconductor. Variations in electrical characteristics, optical behavior, and even device operation can come from this non-uniformity. To improve the functionality and dependability of electronic devices and optoelectronic applications, p-type and n-type semiconducting thin films must undergo Atomic Layer Deposition (ALD). Furthermore, the production of flaws inside ZnO thin films is a significant challenge. Electrical conductivity, carrier mobility, and optical transparency can all be harmed by defects such as vacancies, interstitials, and grain boundaries. Controlling and minimizing flaws necessitates fine-tuning of deposition parameters, growth rates, and post-deposition annealing processes, all of which necessitate a thorough understanding of material behavior and interfacial phenomena.

To address these issues, intricate control over process parameters, extensive characterization techniques, and a multidisciplinary approach combining materials science, physics, and engineering are required. The changing nature of deposition technologies, as well as the requirement for specialized equipment and knowledge, complicate research and development efforts. A significant problem is establishing appropriate crystalline structure and orientation. Because the characteristics of ZnO are highly reliant on crystallographic alignment, it is critical to drive development in favored crystal directions for specific purposes. Misalignment or unexpected crystal phases might affect device performance or optical characteristics. Among the principal difficulties are:

1) Precursor Reactivity and Surface Chemistry: It can be difficult to choose the right precursor compounds for p-type and n-type doping. For precise dopant incorporation and film uniformity, it is essential to achieve self-limiting and selective surface reactions while preventing unwanted side reactions [18].
2) Achieving the correct carrier concentration and electrical characteristics depends on the activation efficiency of the dopant atoms in the films deposited. For some dopant species, improving dopant activation while reducing defects contin-

ues to be a serious problem [19].

3) To customize the electrical characteristics of p-type and n-type semiconducting thin films, precise control over dopant content and distribution profiles is required. For the best device performance, dopant diffusion during the deposition and annealing processes must be understood and managed.
4) Defect Control and Trap States: Trap states and dangling bonds are two defects that can have a big impact on how well carriers are transported in semiconductor thin films. For improving charge carrier mobility and overall device performance, fault densities must be reduced [25].
5) The performance of electrical devices is significantly influenced by the interface between p-type and n-type semiconductors, according to interface engineering. At heterojunctions, it is difficult to minimize energy barriers while ensuring effective carrier injection and extraction [26].
6) The integration of high-k dielectrics with p- and n-type semiconductors to create gate stacks for field-effect transistors presents issues with interfacial quality, charge trapping, and reliability.
7) Compatibility with Device Processing: For effective device integration and scalability, ALD procedures must be compatible with other device manufacturing phases like lithography, etching, and metallization.
8) Cost and Throughput: The standard ALD deposition method is slow and precise, which can have an impact on the price and throughput of large-scale semiconductor fabrication. For industrial adoption, it is essential to address these factors [27].
9) Concerns about the environment and safety: Some precursor materials used in ALD procedures may be dangerous or harmful to the environment. For industrial-scale commercial applications, it is crucial to develop sustainable and secure ALD methods.

Continuous advancement in ALD methods, precursor chemistry, and process optimization are necessary to meet these problems. To improve the field of ALD for p-type and n-type semiconducting thin films and make it possible to realize cutting-edge electronic devices and new technologies, interdisciplinary cooperation and creative solutions are also essential [20].

7. Discussion

The reviewed literature highlights significant progress in thin-film deposition strategies for ZnO-based semiconductors, yet consistent challenges remain that influence film performance, reproducibility, and device integration. Across studies, deposition techniques including RF sputtering, sol–gel processing, PLD, and ALD demonstrate notable advantages in controlling thickness, crystallinity, stoichiometry, and dopant incorporation. Table 1 shows the comparative table of thin films deposition techniques. However, the overall comparison reveals that each method presents inherent limitations related to precursor behavior, interfacial reactions, and microstructural evolution. These factors collectively shape the electrical and optical functionality of ZnO thin films [28].

A central theme emerging from the review is the persistent difficulty of achieving reliable p-type ZnO, regardless of deposition technique. Studies consistently report issues linked to deep acceptor levels, self-compensation, and instability under ambient conditions. In contrast, n-type ZnO films are more easily obtained, although carrier concentration and mobility still depend strongly on oxygen partial pressure, substrate temperature, and post-deposition annealing [29]. These observations underscore the need for improved dopant selection, tighter control of growth conditions, and advanced defect-engineering strategies [29].

Atomic Layer Deposition (ALD) has gained prominence due to its exceptional thickness, uniformity, conformity over complex topographies, and atomic-scale precision in doping. Nevertheless, reported challenges include precursor instability, carbon contamination, impurity incorporation, and limited dopant activation for both p-type and n-type films [30]. The literature indicates that ALD performance is highly sensitive to precursor chemistry and surface kinetics, which directly influence film crystallinity and electrical behavior. Moreover, achieving high-quality p-type films through ALD remains limited by dopant solubility and the tendency for compensating native defects.

Despite these constraints, ALD-grown ZnO and doped ZnO thin films demonstrate strong potential for integration into high-performance optoelectronic and energy-related applications [31]. Studies show successful implementation in transparent electronics, gas sensors, UV photodetectors, memory devices, and thin-film transistors, where conformal coating and precise thickness control are essential. The emergence of ALD-based heterostructures and hybrid architecture further highlights its relevance in next-generation flexible and nanoscale device platforms.

In comparing ALD with other deposition methods, the review identifies a trade-off between precision and throughput. While sputtering and PLD offer faster deposition and scalable industrial processing, they often struggle with uniformity and dopant distribution. ALD, although slower, provides unmatched controllability that is particularly advantageous for nanoscale electronics and 3D device structures [32]. This comparative perspective emphasizes that no single technique is universally

Table 1. Comparative table of thin films deposition techniques.

Technique	Principle	Film Thickness Control	Film Uniformity	Applications
• PVD (Physical Vapor Deposition)	Evaporation or sputtering of material	Good	Good	Optics, Electronics, Coatings
• CVD (Chemical Vapor Deposition)	Chemical reactions for deposition	Good	Good	Semiconductors, Coatings
• ALD (Atomic Layer Deposition)	Sequential self-limiting reactions	Excellent	Excellent	Nanotechnology, Semiconductors
• MBE (Molecular Beam Epitaxy)	Precise atom/molecule deposition	Excellent	Excellent	Semiconductors, Quantum Dots
• Sputtering	Ejection from target material	Good	Good	Electronics, Optics, Coatings
• Spin Coating	Liquid precursor spun onto substrate	Limited	Fair	Polymer Films, Photolithography
• Sol-Gel Deposition	Formation from colloidal solution	Limited	Fair	Oxide Films, Optical Coatings
• Electroplating/Electrochemical Deposition	Deposition via electric current	Limited	Fair	Metal Coatings, Interconnects

optimal; instead, technique selection must align with the specific device requirements and application environment.

Overall, the synthesis of current research indicates that future advancements in ZnO-based semiconductor films will depend on improving precursor chemistry, achieving stable p-type doping, minimizing defect-related scattering, and enhancing compatibility with flexible and large-area substrates [4]. Continued progress in ALD process development, especially in tailoring surface reactions and dopant incorporation pathways, will be essential to realizing high-performance semiconductor films. While notable progress has been made, the field still faces significant challenges that define important opportunities for future research.

Overall, this review identifies ALD as the most precise and controllable technique for engineering doped ZnO thin films. While n-type ZnO has reached maturity, stable p-type ZnO still faces fundamental challenges making dopant activation, defect control, and interface engineering the key priorities for future research [33].

8. Conclusion

Finally, the investigation of thin film deposition processes for ZnO-based semiconductors provides a detailed understanding of their numerous benefits, problems, and potential future prospects. The benefits of these approaches, as demonstrated by the case study, highlight their critical role in semiconductor manufacturing. The ability to precisely adjust layer thickness, crystal structure, and material composition improves the optimization of critical electrical and optical properties for semiconductor applications. Furthermore, the adaptability of these processes enables the deposition of ZnO films on a variety of substrates, allowing integration into a wide range of devices ranging from photo detectors to thin-film transistors. However, problems in achieving uniformity on complicated surfaces and minimizing flaws persist. While progress has been made, these issues continue to fuel continuing research efforts targeted at improving deposition methods and reducing impurities. The demand for industrial-scale repeatability and cost-effectiveness drives the exploration of novel techniques even further. The research also reveals the bright future potential of thin film deposition for ZnO-based semiconductors. Continuous breakthroughs in deposition processes, fueled by developing materials and novel precursors, have the ability to solve existing problems. Understanding ZnO growth mechanisms in greater depth paves the path for even greater precision in controlling film characteristics and minimizing flaws. The seamless integration of ZnO-based thin films with developing technologies such as flexible electronics and transparent screens opens up a new world of possibilities.

9. Declarations

9.1. Author Contributions

Md Nazmul Haque reviewed relevant journal papers and collected information. **Md Yakub Ali Khan** reviewed relevant journal papers and combined all information. **Md Nazmul Haque** and **Md Yakub Ali Khan** wrote this manuscript together and made final draft. **Md Nazmul Haque** revised it and make final version of manuscript.

9.2. Institutional Review Board Statement

Not applicable.

9.3. Informed Consent Statement

Not applicable.

9.4. Data Availability Statement

We wrote this manuscript by reviewing others manuscript which are added in reference section.

9.5. Acknowledgment

Not applicable.

9.6. Conflicts of Interest

The authors declare no conflicts of interest.

10. References

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