

ZnTe Thin Films: Deposition Methods, Physical Properties, and Device Prospects

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Abstract: Zinc telluride (ZnTe) is a II–VI compound semiconductor with a direct wide band gap (~2.26 eV at room temperature), high optical absorption coefficient, and good chemical stability. These properties make ZnTe thin films highly attractive for applications in optoelectronics, including photodetectors, solar cells, light-emitting devices, transparent electronics, and heterojunction structures. In recent years, considerable research efforts have been devoted to the growth, doping, characterization, and device integration of ZnTe thin films using various physical and chemical deposition techniques. This review provides a comprehensive overview of ZnTe thin films, covering crystal structure, fundamental properties, deposition methods, doping strategies, defects and transport mechanisms, characterization techniques, and major applications. Current challenges and future research directions are also discussed, with particular emphasis on improving film quality, electrical conductivity, and device performance.

Keywords: ZnTe, Thin Films, Optoelectronic, Photodetector and Solar Cell.

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I. INTRODUCTION

Wide band gap semiconductors have emerged as key materials for next-generation optoelectronic and photonic devices due to their ability to operate under high electric fields, elevated temperatures, and high-energy photon environments. These materials exhibit strong optical absorption, high transparency in selected spectral regions, and improved thermal and chemical stability, making them suitable for applications such as photodetectors, light-emitting diodes, laser diodes, and solar energy conversion devices. Among the II–VI group of compound semiconductors, zinc telluride (ZnTe) has attracted considerable attention owing to its unique combination of physical, optical, and electronic properties [1].

ZnTe is a direct band gap semiconductor with a room-temperature band gap of approximately 2.26 eV, which enables efficient absorption and emission of visible light. The direct nature of the band gap allows strong optical transitions without the need for phonon assistance, resulting in high absorption coefficients typically exceeding 10^4 – 10^5 cm^{-1} near the absorption edge. This characteristic makes ZnTe thin films particularly attractive for optoelectronic applications requiring efficient light–matter interaction. Furthermore, ZnTe exhibits good chemical stability and favorable band alignment with several II–VI and III–V

semiconductors, including CdTe, CdS, ZnO, and GaAs, which facilitates its integration into heterostructure devices [2].

In thin-film photovoltaic technology, ZnTe has been extensively explored as a window layer, buffer layer, back contact material, and, in some configurations, as an absorber layer. In CdTe-based solar cells, ZnTe is commonly employed as a back contact or interfacial layer due to its p-type conductivity and suitable valence band alignment with CdTe, which reduces contact resistance and enhances hole transport. Beyond photovoltaic applications, ZnTe thin films have demonstrated promising performance in visible and near-UV photodetectors, light-emitting diodes, electro-optic modulators, and nonlinear optical devices. The tunability of ZnTe properties through thickness control, doping, and heterojunction formation further broadens its technological relevance.

Despite these advantages, the widespread application of ZnTe thin films remains limited by several material and device-related challenges. One of the primary issues is the relatively low carrier mobility in polycrystalline ZnTe thin films, which is often attributed to grain boundary scattering and defect-induced carrier trapping. Achieving stable and reproducible electrical conductivity—either p-type or n-type—also remains a significant challenge due to self-

compensation effects and the presence of intrinsic defects such as zinc vacancies and tellurium antisites. These defects can act as non-radiative recombination centers, leading to reduced carrier lifetime and degraded device performance.

To address these limitations, extensive research efforts have been directed toward optimizing deposition techniques, post-deposition treatments, and doping strategies. Both physical and chemical deposition methods have been investigated to improve crystallinity, stoichiometric control, and surface morphology. Post-deposition annealing and controlled doping using transition metals or non-metallic elements have been employed to tailor the optical band gap, enhance carrier concentration, and suppress defect-related recombination. This review aims to critically summarize the progress achieved in ZnTe thin film research, highlighting recent advancements in material synthesis, property engineering, and device integration, while identifying key challenges and future research directions necessary for the development of high-performance ZnTe-based optoelectronic devices [2], [3], [4].

II. CRYSTAL STRUCTURE AND BASIC PROPERTIES OF ZNTE

Zinc telluride (ZnTe) is a II–VI compound semiconductor that exhibits well-defined crystalline phases, which play a crucial role in determining its optical, electrical, and mechanical properties. Under ambient conditions, ZnTe predominantly crystallizes in the cubic zinc blende (sphalerite) structure, which belongs to the space group $F-43m$. In this structure, each zinc atom is tetrahedrally coordinated to four tellurium atoms, and each tellurium atom is similarly coordinated to four zinc atoms, resulting in a highly symmetric and stable crystal lattice. The tetrahedral coordination leads to strong covalent bonding with partial ionic character, contributing to the material's favorable electronic and optical behavior. The lattice constant of cubic ZnTe is approximately 6.10 Å at room temperature, which enables reasonable lattice matching with several technologically important semiconductor materials such as CdTe, CdS, and GaAs. This lattice compatibility is particularly advantageous for the fabrication of heterojunction devices and multilayer structures, where reduced lattice mismatch helps minimize interfacial strain, dislocation density, and defect formation. As a result, ZnTe is frequently employed as a buffer or interfacial layer in thin-film photovoltaic and optoelectronic devices. In addition to the stable cubic phase, ZnTe can also form metastable crystal structures such as the hexagonal wurtzite phase under specific growth conditions. These conditions include low-temperature deposition, high growth rates, non-equilibrium synthesis methods, or growth on lattice-mismatched substrates. The wurtzite phase of ZnTe exhibits different symmetry and anisotropic properties compared to the zinc blende phase, which can influence carrier transport, optical polarization, and phonon behavior. Although less common, the presence of mixed phases or phase transitions in ZnTe thin films can significantly affect material performance, particularly in nanoscale and thin-film systems. The crystal structure of ZnTe directly

influences its fundamental physical properties. ZnTe is a direct band gap semiconductor with a band gap energy of approximately 2.26 eV at room temperature, originating from electronic transitions at the Brillouin zone center (Γ point). The cubic zinc blende structure supports strong optical transitions, resulting in high absorption coefficients in the visible spectral range. Optical properties such as band gap energy, refractive index, and absorption edge are highly sensitive to crystal quality, crystallite size, and strain within the lattice. From an electrical perspective, ZnTe typically exhibits intrinsic p-type conductivity due to native defects, primarily zinc vacancies, which act as acceptor states. The concentration and distribution of these defects are closely related to the crystal structure and growth conditions of the thin films. Structural imperfections such as grain boundaries, stacking faults, and dislocations—common in polycrystalline ZnTe thin films—can act as carrier scattering centers, reducing carrier mobility and increasing electrical resistivity. Furthermore, structural parameters such as crystallite size and lattice strain, often extracted from X-ray diffraction analysis, X-ray diffraction (XRD) is the most widely used technique to investigate the crystal structure, phase purity, and preferred orientation of ZnTe thin films. ZnTe deposited under ambient conditions typically exhibits a cubic zinc blende structure, and its diffraction pattern can be well indexed according to the standard JCPDS/ICDD database (commonly PDF No. 15-0746) [2]. The presence of sharp and well-defined diffraction peaks confirms the crystalline nature of the films, while the absence of secondary peaks indicates phase purity without detectable elemental Zn, Te, or oxide-related phases. For cubic ZnTe thin films, the most prominent diffraction peak is generally observed at a 2θ value of approximately 25.3° , corresponding to the (111) crystallographic plane. This reflection is often the strongest peak in polycrystalline ZnTe films, indicating a preferred (111) orientation, which is energetically favorable due to its lowest surface energy in the zinc blende structure. The dominance of the (111) plane is commonly reported for ZnTe films deposited by chemical bath deposition, thermal evaporation, sputtering, and electrodeposition techniques. Additional characteristic diffraction peaks of cubic ZnTe are typically observed at $2\theta \approx 41.9^\circ$, 49.7° , and 66.4° , which can be indexed to the (220), (311), and (400) planes, respectively. In some cases, weaker reflections corresponding to higher-index planes such as (331) or (422) may also appear, depending on the deposition method, film thickness, and post-deposition annealing conditions. The observed peak positions closely match standard ZnTe data, confirming the formation of the zinc blende phase [3], [5], [6]. The crystallite size of ZnTe thin films can be estimated from the full width at half maximum (FWHM) of the dominant diffraction peaks, typically the (111) reflection, using the Debye–Scherrer equation. Narrower peak widths indicate larger crystallite sizes and improved crystallinity, while peak broadening suggests nanoscale grain size and lattice strain. Any systematic shift in peak positions relative to standard values may indicate lattice distortion caused by residual stress, dopant incorporation, or non-stoichiometry within the film. Furthermore, the lattice parameter of cubic ZnTe can be calculated from the indexed diffraction peaks using Bragg's

law and the cubic lattice relationship. Values close to the standard lattice constant ($\sim 6.10 \text{ \AA}$) suggest good stoichiometric control and minimal structural distortion. Deviations from this value may arise due to defects, dopant atoms, or strain induced by substrate mismatch. Overall, XRD analysis provides crucial insight into the structural quality, phase stability, and orientation of ZnTe thin films.

The clear identification of characteristic ZnTe diffraction peaks and their corresponding Miller indices confirms the successful formation of the cubic zinc blende structure, which is essential for achieving optimal optical and electrical performance in ZnTe-based optoelectronic devices.

Table 1 Commonly Reported XRD Peaks of Cubic ZnTe

2θ (degrees)	Plane (hkl)
$\sim 25.3^\circ$	(111)
$\sim 41.9^\circ$	(220)
$\sim 49.7^\circ$	(311)
$\sim 66.4^\circ$	(400)

III. ELECTRICAL PROPERTIES OF ZNTE THIN FILMS

The electrical properties of zinc telluride (ZnTe) thin films play a crucial role in determining their suitability for optoelectronic and electronic device applications. Undoped ZnTe typically exhibits intrinsic p-type conductivity, which is primarily attributed to native point defects formed during growth. Among these defects, zinc vacancies act as shallow acceptor states and are widely recognized as the dominant source of p-type behavior in ZnTe. The formation of these vacancies is energetically favorable under tellurium-rich growth conditions, leading to hole generation without intentional doping.

Despite this inherent p-type nature, ZnTe thin films often suffer from relatively high electrical resistivity, which limits their practical implementation in devices such as photodetectors, solar cells, and light-emitting diodes. The high resistivity is commonly associated with low free-carrier concentration and poor carrier mobility, particularly in polycrystalline thin films. In chemically deposited or low-temperature grown ZnTe films, incomplete crystallization and non-stoichiometry further exacerbate this issue by increasing defect density [5], [7], [8]. Carrier concentration in ZnTe thin films is strongly influenced by intrinsic defects, including zinc vacancies, tellurium interstitials, and antisite defects. While zinc vacancies contribute to hole generation, excessive defect density can introduce deep trap states that act as recombination centers, reducing effective carrier concentration and carrier lifetime. Additionally, self-compensation effects, arising from the simultaneous formation of donor- and acceptor-type defects, often hinder precise control over electrical conductivity. This self-compensation is one of the major challenges in achieving reproducible and stable electrical properties in ZnTe. Carrier mobility in ZnTe thin films is typically limited by grain boundary scattering, defect scattering, and phonon interactions. Polycrystalline ZnTe films consist of numerous grains separated by grain boundaries that act as potential barriers to carrier transport. These grain boundaries can trap charge carriers, leading to localized band bending and reduced mobility. As a result, ZnTe thin films generally exhibit lower mobility values compared to their single-crystal counterparts. Film thickness, grain size, and surface roughness significantly affect mobility, with thicker films

and larger grains generally showing improved electrical transport. Dopant incorporation has been extensively explored as a strategy to improve the electrical properties of ZnTe thin films. Acceptor dopants such as copper (Cu), nitrogen (N), and phosphorus (P) have been used to enhance p-type conductivity by increasing hole concentration. Transition-metal dopants, including manganese (Mn), iron (Fe), and cobalt (Co), have also been investigated for their ability to modify carrier concentration and introduce localized energy levels within the band gap. While doping can effectively reduce resistivity and enhance conductivity, excessive dopant concentration may increase defect density and carrier scattering, resulting in reduced mobility. Electrical characterization techniques such as Hall effect measurements, current-voltage (I-V) analysis, and temperature-dependent conductivity studies are commonly employed to evaluate carrier type, concentration, and mobility in ZnTe thin films. Overall, optimizing the electrical properties of ZnTe requires a careful balance between defect control, grain boundary engineering, and controlled doping. Continued research in this area is essential to overcome resistivity limitations and fully exploit ZnTe thin films in high-performance optoelectronic devices [4].

IV. OPTICAL PROPERTIES OF ZNTE THIN FILMS

Zinc telluride (ZnTe) is a direct band gap semiconductor with a room-temperature band gap energy of approximately 2.26 eV, which places its optical response in the visible region of the electromagnetic spectrum. The direct nature of the band gap implies that electronic transitions between the valence band maximum and the conduction band minimum occur at the same momentum (Γ point), allowing efficient photon absorption and emission without phonon assistance. This characteristic makes ZnTe thin films particularly attractive for optoelectronic devices such as photodetectors, light-emitting diodes, and photovoltaic components. One of the most notable optical features of ZnTe is its high absorption coefficient, which typically exceeds 10^4 – 10^5 cm^{-1} near the fundamental absorption edge. Such strong absorption enables effective light harvesting even in relatively thin films, making ZnTe suitable for thin-film device architectures. The absorption behavior of ZnTe thin films is commonly studied using UV–

Visible spectroscopy, where a sharp absorption edge is indicative of good crystalline quality and minimal structural disorder. The optical band gap is usually determined from Tauc plots by extrapolating the linear region of $(\alpha h\nu)^2$ versus photon energy ($h\nu$), confirming the direct allowed transition nature of ZnTe. The optical band gap of ZnTe thin films is highly sensitive to film thickness, crystallinity, and grain size. In nanocrystalline or ultrathin films, a slight blue shift in band gap energy is often observed due to quantum confinement effects and increased carrier localization. Conversely, thicker films with improved crystallinity and larger grain sizes generally exhibit band gap values closer to the bulk ZnTe value. Structural defects, lattice strain, and non-stoichiometry can also cause band gap fluctuations by introducing localized states within the forbidden energy gap.

In addition to band gap energy, other important optical constants such as the refractive index (n) and extinction coefficient (k) play a critical role in determining the optical response of ZnTe thin films. The refractive index of ZnTe is relatively high in the visible region, which is advantageous for optical confinement and waveguiding applications. Variations in refractive index are strongly correlated with film density, surface roughness, and microstructural uniformity. The extinction coefficient, which represents optical losses due to absorption and scattering, is influenced by defect density and surface morphology. The deposition technique employed for ZnTe thin film growth has a significant impact on optical properties. Films deposited using high-vacuum physical methods such as molecular beam epitaxy and sputtering typically show sharper absorption edges and lower optical losses due to superior crystalline quality. In contrast, chemically deposited ZnTe films may exhibit broader absorption edges as a result of increased defect density and grain boundary effects. However, post-deposition treatments such as thermal annealing can substantially improve optical transparency, reduce defect states, and enhance absorption characteristics [9], [10], [11]. Photoluminescence (PL) spectroscopy is often used to further investigate the optical quality of ZnTe thin films. Near-band-edge emission is commonly observed in high-quality films, while deep-level emissions are associated with intrinsic defects such as zinc vacancies and tellurium interstitials. Overall, the optical properties of ZnTe thin films are strongly governed by growth conditions and microstructural parameters. Optimizing these factors is essential for achieving high optical performance and enabling the effective use of ZnTe thin films in advanced optoelectronic and photonic devices [12].

V. DEPOSITION TECHNIQUES FOR ZNTE THIN FILMS

A wide range of deposition techniques has been employed for the growth of ZnTe thin films, as the choice of fabrication method plays a decisive role in determining film morphology, crystallinity, stoichiometry, and resulting optical and electrical properties. Both physical and chemical deposition techniques have been extensively explored to tailor ZnTe thin films for specific optoelectronic applications. Each technique offers distinct advantages and

limitations with respect to film quality, scalability, cost, and process control.

➤ Physical Deposition Techniques for ZnTe Thin Films

Physical deposition techniques are extensively employed for the fabrication of high-quality ZnTe thin films due to their ability to provide good control over film thickness, composition, and crystalline structure. These methods typically involve the physical transfer of material from a solid source to a substrate under controlled vacuum conditions, enabling the growth of uniform and dense thin films. Among the various physical techniques, thermal evaporation, electron beam evaporation, sputtering, and molecular beam epitaxy (MBE) are the most commonly used for ZnTe thin film deposition [1].

Thermal evaporation is one of the simplest and most widely used physical deposition methods. In this technique, ZnTe or its constituent elements are heated in a high-vacuum environment until they evaporate and condense onto a substrate. Thermal evaporation offers advantages such as ease of operation, low deposition temperature, and good control over film thickness. ZnTe films deposited by thermal evaporation generally exhibit polycrystalline structure with preferential orientation depending on substrate type and temperature. However, maintaining precise stoichiometry can be challenging due to the difference in vapor pressures of zinc and tellurium, which may lead to compositional deviations and defect formation [13].

Electron beam evaporation overcomes some of the limitations of thermal evaporation by using a focused high-energy electron beam to evaporate the source material. This method allows the deposition of high-melting-point materials and provides better control over evaporation rate and film uniformity. ZnTe thin films grown by electron beam evaporation often exhibit improved adhesion and higher density compared to thermally evaporated films. Nevertheless, the energetic electrons may induce localized heating and defects in the growing film, which requires careful optimization of deposition parameters [14].

Sputtering techniques, including radio-frequency (RF) and direct-current (DC) magnetron sputtering, are widely employed for ZnTe thin film growth due to their excellent reproducibility and uniformity over large areas. In sputtering, energetic ions bombard a ZnTe target, ejecting atoms that deposit onto the substrate. This method allows better control over film composition and thickness and is compatible with industrial-scale production. Sputtered ZnTe films often exhibit good adhesion and dense microstructure; however, high-energy ion bombardment may introduce lattice defects and stress, potentially affecting electrical and optical properties unless optimized through substrate heating or post-deposition annealing.

Among physical techniques, molecular beam epitaxy (MBE) is considered the most advanced method for depositing ZnTe thin films. MBE operates under ultra-high vacuum conditions and allows atomic-level control over growth parameters, enabling the epitaxial growth of ZnTe

films with exceptionally low defect density. This technique is particularly valuable for fabricating high-quality heterostructures and quantum wells. However, the requirement for ultra-high vacuum systems, precise flux control, and slow growth rates significantly increases fabrication cost and limits large-scale application [15].

Overall, physical deposition techniques provide superior control over film quality and are essential for fundamental studies and high-performance ZnTe-based devices. However, their high capital cost and complex instrumentation motivate ongoing research into optimizing these methods and developing cost-effective alternatives [2].

Table 2 Comparison of Physical Deposition Techniques for ZnTe Thin Films

Deposition Technique	Working Principle	Film Quality & Crystallinity	Advantages	Limitations	Typical Applications
Thermal Evaporation	Heating of ZnTe or elemental sources under high vacuum; vapor condenses on substrate	Polycrystalline; moderate crystallinity	Simple setup, low cost, good thickness control	Poor stoichiometric control due to different vapor pressures of Zn and Te	Optical coatings, preliminary optoelectronic studies
Electron Beam Evaporation	High-energy electron beam evaporates source material	Improved density and crystallinity compared to thermal evaporation	Suitable for high-melting materials, better uniformity	Equipment cost, possible electron-induced defects	High-quality optical and electronic thin films
RF/DC Magnetron Sputtering	Ionized gas ions sputter atoms from ZnTe target	Dense, uniform films; good reproducibility	Excellent adhesion, large-area deposition, good composition control	Ion bombardment-induced stress and defects	Industrial-scale coatings, optoelectronic devices
Molecular Beam Epitaxy (MBE)	Atomic beams deposited under ultra-high vacuum	Epitaxial, single-crystal, very low defect density	Precise thickness and composition control, high purity	Very high cost, slow growth, complex instrumentation	Quantum devices, heterostructures, fundamental research

➤ Chemical Deposition Techniques for ZnTe Thin Films

Chemical deposition techniques have emerged as attractive alternatives to physical methods for the fabrication of ZnTe thin films, primarily due to their cost effectiveness, simplicity, and suitability for large-area and low-temperature processing. These methods are particularly advantageous for applications where scalability and economic viability are critical, such as thin-film photovoltaics and large-area optoelectronic devices. Among the various chemical techniques explored for ZnTe thin film growth, chemical bath deposition (CBD), electrodeposition, spray pyrolysis, and successive ionic layer adsorption and reaction (SILAR) are the most widely investigated [6].

Chemical bath deposition (CBD) has received significant attention for ZnTe thin film fabrication owing to its low processing temperature, ease of operation, and ability to coat substrates with complex shapes. In CBD, ZnTe films are formed through controlled chemical reactions in an aqueous or non-aqueous solution, where metal and chalcogenide ions slowly react and precipitate onto the substrate surface. The growth rate and film properties can be effectively tuned by adjusting bath parameters such as precursor concentration, pH, temperature, and deposition time. CBD-grown ZnTe films typically exhibit uniform coverage and good adhesion; however, they often possess a polycrystalline or nanocrystalline structure with relatively high defect density. Post-deposition annealing is commonly employed to enhance crystallinity, reduce defects, and improve optical and electrical properties [5].

Electrodeposition is another promising chemical technique that enables controlled ZnTe thin film growth by applying an external potential to drive the reduction of metal ions from an electrolyte onto a conductive substrate. This method offers excellent control over film thickness, composition, and morphology through precise adjustment of deposition voltage, current density, and bath composition. Electrodeposition is particularly attractive for ZnTe fabrication due to its low cost, high material utilization efficiency, and compatibility with large-area substrates. However, achieving uniform stoichiometry and minimizing impurity incorporation remain challenges that require careful optimization of deposition conditions [16].

Spray pyrolysis involves spraying a precursor solution onto a heated substrate, where thermal decomposition leads to the formation of ZnTe thin films. This technique is simple, scalable, and suitable for large-area deposition, making it attractive for industrial applications. ZnTe films deposited by spray pyrolysis often exhibit good uniformity, though crystallinity may be limited by relatively low substrate temperatures. Post-deposition thermal treatments are typically necessary to improve grain growth and reduce structural defects.

Successive ionic layer adsorption and reaction (SILAR) is a layer-by-layer deposition technique that involves the alternate adsorption of cations and anions onto the substrate surface. SILAR allows precise control over film thickness and composition by adjusting the number of deposition cycles. ZnTe thin films prepared by SILAR

generally show good thickness uniformity and strong substrate adhesion, but like other chemical methods, they may initially exhibit lower crystallinity.

Overall, chemical deposition techniques provide flexible and economically viable routes for ZnTe thin film

fabrication. Although films deposited by these methods often exhibit lower crystallinity compared to those grown by physical techniques, post-deposition annealing and process optimization can significantly enhance film quality, making chemical methods highly promising for scalable ZnTe-based optoelectronic devices [17].

Table 3 Comparison of Chemical Deposition Techniques for ZnTe Thin Films

Deposition Technique	Working Principle	Typical Film Characteristics	Advantages	Limitations	Typical Applications
Chemical Bath Deposition (CBD)	Controlled precipitation of Zn and Te ions from solution onto substrate	Polycrystalline or nanocrystalline; uniform coverage	Low cost, low temperature, simple setup, large-area deposition	Lower crystallinity, higher defect density	Photodetectors, buffer layers, solar cell components
Electrodeposition	Electrochemical reduction of Zn and Te ions on conductive substrate	Dense films with controlled thickness	Excellent thickness control, high material utilization, scalable	Requires conductive substrates, stoichiometry control	Thin-film photovoltaics, optoelectronic devices
Spray Pyrolysis	Thermal decomposition of sprayed precursor solution on heated substrate	Uniform films; moderate crystallinity	Simple, scalable, suitable for large-area coatings	Requires high substrate temperature, post-annealing	Optical coatings, solar absorbers
SILAR	Alternate adsorption of cations and anions in solution	Layer-by-layer growth; good thickness uniformity	Precise thickness control, low-cost, low temperature	Initial low crystallinity, longer deposition time	Nanostructured films, optoelectronics

VI. DOPING OF ZNTE THIN FILMS

Doping plays a crucial role in tailoring the electrical, optical, and magnetic properties of ZnTe thin films, enabling their effective use in optoelectronic and electronic devices. While undoped ZnTe typically exhibits intrinsic p-type conductivity due to native defects such as zinc vacancies, the resulting carrier concentration and mobility are often insufficient for high-performance applications. Consequently, both intrinsic defect engineering and extrinsic doping strategies have been widely explored to enhance carrier concentration, reduce resistivity, and modify band structure. The effectiveness of doping in ZnTe strongly depends on dopant type, concentration, incorporation mechanism, and growth conditions.

➤ Transition Metal Doping

Transition metal doping has attracted significant interest as a means of modifying the electronic structure and functional properties of ZnTe thin films. Elements such as manganese (Mn), copper (Cu), iron (Fe), and cobalt (Co) have been incorporated into the ZnTe lattice either by substituting Zn sites or occupying interstitial positions. These dopants introduce localized electronic states within the ZnTe band gap, leading to changes in optical absorption, electrical conductivity, and magnetic behavior. Among transition metals, Mn-doped ZnTe has been extensively investigated due to its ability to tune the band gap and induce diluted magnetic semiconductor (DMS) behavior. The incorporation of Mn²⁺ ions into Zn²⁺ lattice sites introduces localized d-states, which interact with the host

semiconductor bands through exchange interactions. This interaction can result in band gap modification, enhanced visible-light absorption, and improved photoresponse, making Mn-doped ZnTe particularly promising for photodetectors and spintronic devices. Additionally, Mn doping can influence crystallite size, lattice strain, and defect density, thereby indirectly affecting carrier transport properties. Copper doping is commonly employed to enhance p-type conductivity in ZnTe thin films, as Cu acts as an effective acceptor dopant. Cu incorporation increases hole concentration and reduces resistivity, which is beneficial for applications such as back contacts in CdTe solar cells. However, excessive transition metal doping can introduce deep trap states and increase carrier scattering, leading to reduced mobility and degraded device performance. Therefore, careful optimization of dopant concentration is essential [6].

➤ Non-Metal and Group V Doping

Non-metal and Group V dopants such as nitrogen (N) and phosphorus (P) have been explored as acceptor dopants to achieve stable and reproducible p-type conductivity in ZnTe thin films. These dopants typically substitute for tellurium sites and introduce shallow acceptor levels near the valence band maximum. Nitrogen doping, in particular, has shown promise due to its relatively small atomic size and ability to form acceptor states that enhance hole concentration.

Despite these advantages, achieving efficient dopant activation remains challenging due to strong self-

compensation effects in ZnTe. The formation of compensating donor-like defects, such as tellurium vacancies or interstitial zinc atoms, can neutralize the effect of acceptor dopants and limit conductivity improvement. Furthermore, low solubility of Group V dopants and their tendency to form complexes or secondary phases further complicate doping control.

Overall, doping remains a critical yet challenging strategy for optimizing ZnTe thin films. Continued advances in growth techniques, dopant incorporation methods, and post-deposition treatments are essential to achieve precise control over electrical and optical properties, enabling the development of high-performance ZnTe-based optoelectronic and spintronic devices [18].

VII. DEFECTS, GRAIN BOUNDARIES, AND TRANSPORT MECHANISMS IN ZNTE THIN FILMS

The performance and reliability of ZnTe thin films are strongly governed by the presence of intrinsic defects, secondary phases, and microstructural features such as grain boundaries. These factors play a critical role in determining charge carrier generation, transport, and recombination processes, thereby directly influencing the optical and electrical behavior of ZnTe-based devices. Understanding defect formation and transport mechanisms is therefore essential for optimizing ZnTe thin films for optoelectronic applications. Intrinsic point defects commonly observed in ZnTe include zinc vacancies, tellurium antisites and interstitial defects. Zinc vacancies are energetically favorable under tellurium-rich growth conditions and act as acceptor states, contributing to the intrinsic p-type conductivity of ZnTe. However, an excessive concentration of zinc vacancies can introduce deep-level trap states that act as non-radiative recombination centers, reducing carrier lifetime and quantum efficiency. Tellurium antisite defects, where Te atoms occupy Zn lattice sites, can also introduce deep defect levels within the band gap, further enhancing recombination losses. Interstitial defects, such as zinc or tellurium atoms occupying interstitial positions, arise due to non-stoichiometric growth or rapid deposition rates. These defects often behave as compensating centers, neutralizing the effect of intentional dopants and limiting effective carrier concentration. In addition, secondary phases or elemental clusters may form under poor stoichiometric control, particularly in chemically deposited ZnTe thin films, leading to degraded electrical and optical properties. Grain boundaries are a dominant microstructural feature in polycrystalline ZnTe thin films deposited by most chemical and low-temperature physical methods. These grain boundaries act as charge trapping and scattering centers, creating localized potential barriers that impede carrier transport. Trapped charges at grain boundaries can cause band bending and carrier depletion regions, which significantly reduce carrier mobility [19]. As a result, polycrystalline ZnTe films typically exhibit lower electrical conductivity compared to single-crystal or epitaxial ZnTe. Charge transport in ZnTe thin films is governed by a combination of mechanisms, depending on temperature,

defect density, and microstructure. At higher temperatures, thermally activated band conduction dominates, whereas at lower temperatures or in highly defective films, transport may occur through hopping or tunneling between localized states. Grain boundary-controlled transport models, such as the Seto model, are often used to describe electrical conduction in polycrystalline ZnTe, where the effective mobility is limited by grain boundary potential barriers. The influence of defects and grain boundaries can be mitigated through optimized growth conditions and post-deposition treatments. Thermal annealing in inert or chalcogen-rich atmospheres has been shown to reduce defect density, promote grain growth, and improve crystallinity. Annealing can also help redistribute dopants and passivate defect states, leading to enhanced carrier mobility and reduced resistivity. Additionally, controlled doping and surface passivation strategies can suppress deep-level defects and improve charge transport across grain boundaries. In summary, defects and grain boundaries play a decisive role in governing transport mechanisms and device performance in ZnTe thin films. Effective defect engineering through precise control of deposition parameters and post-treatment processes is essential to enhance carrier lifetime, mobility, and overall performance of ZnTe-based optoelectronic devices [20].

VIII. APPLICATIONS OF ZNTE THIN FILMS

Zinc telluride (ZnTe) thin films have attracted considerable attention for a wide range of optoelectronic applications owing to their direct band gap, high absorption coefficient in the visible region, and tunable electrical properties. The versatility of ZnTe arises from its ability to be integrated into heterostructures, doped with transition metals or non-metallic elements, and deposited on diverse substrates using various physical and chemical methods. Consequently, ZnTe thin films have been explored extensively in photodetectors, solar cells, and light-emitting devices, where their structural and electronic properties play a critical role in determining device performance.

➤ Photodetectors

ZnTe thin films have demonstrated significant promise as active materials in photodetector devices, particularly for visible and near-ultraviolet (UV) light detection. The direct band gap of approximately 2.26 eV enables efficient absorption of photons in this spectral range, generating electron-hole pairs that contribute to photocurrent. The photoresponse of ZnTe thin films can be further enhanced through intentional doping with transition metals such as manganese or copper, which introduces localized states within the band gap, improves carrier concentration, and extends the absorption spectrum. Additionally, heterojunction formation with materials like cadmium sulfide (CdS) or zinc oxide (ZnO) has been widely employed to improve charge separation, enhance responsivity, and reduce dark current. These heterojunctions enable the efficient collection of photogenerated carriers and are particularly advantageous in thin-film photodetectors, where light absorption must be maximized in sub-micron

layers. Recent studies have also shown that optimizing film thickness, surface morphology, and post-deposition treatments can significantly influence the sensitivity, response time, and spectral selectivity of ZnTe-based photodetectors [10].

➤ Solar Cells

ZnTe is a critical material in thin-film photovoltaic technology, particularly as a back contact or buffer layer in cadmium telluride (CdTe) solar cells. Its favorable valence band alignment with CdTe, combined with intrinsic p-type conductivity, facilitates efficient hole transport and minimizes energy barriers at the interface, leading to improved device efficiency. ZnTe can also act as a buffer layer to reduce interfacial recombination and improve adhesion between CdTe and metallic back contacts. Beyond its role in conventional CdTe-based solar cells, ZnTe has been explored in all-thin-film heterojunction configurations, where it is combined with wide-band-gap n-type semiconductors to create fully transparent or semi-transparent photovoltaic devices. Controlled doping, heterojunction engineering, and post-deposition annealing are often employed to optimize the carrier concentration and electrical conductivity of ZnTe layers, which are essential for minimizing series resistance and enhancing fill factor in solar cells [21].

➤ Light-Emitting and Optoelectronic Devices

The direct band gap and high radiative efficiency of ZnTe make it highly suitable for light-emitting applications. ZnTe thin films have been investigated for use in light-emitting diodes (LEDs), laser diodes, and other optoelectronic devices. Alloying or doping ZnTe with elements such as Mn or Cu enables tuning of emission wavelength and intensity, providing flexibility for device design in the visible and near-UV regions. Additionally, the material's compatibility with other II–VI semiconductors allows the fabrication of multilayer heterostructures and quantum well devices, which can exhibit enhanced emission characteristics due to quantum confinement effects. Optimizing film crystallinity, surface morphology, and defect density is critical to maximizing electroluminescence efficiency and device lifetime.

In summary, ZnTe thin films offer a unique combination of optical and electronic properties that make them highly versatile for advanced optoelectronic applications. Their tunable band gap, p-type conductivity, and ability to form heterojunctions with other semiconductors provide pathways for enhanced performance in photodetectors, solar cells, and light-emitting devices. Continued research focusing on doping strategies, interface engineering, and deposition optimization is expected to expand the applicability of ZnTe thin films in next-generation optoelectronic technologies [18].

Table 4 Applications of ZnTe Thin Films

Application Area	Device Structure / Configuration	Key Properties of ZnTe Layer	Performance Highlights Remarks
Photodetectors	ZnTe / CdS, ZnTe / ZnO heterojunctions	Direct band gap (~2.26 eV), strong visible/near-UV absorption, tunable carrier concentration via doping	Enhanced responsivity and reduced dark current; Mn or Cu doping improves photoresponse and extends spectral range
Solar Cells	ZnTe as back contact or buffer layer in CdTe solar cells; ZnTe / n-type heterojunctions	p-type conductivity, favorable valence band alignment with CdTe, low defect density	Improves hole transport, reduces interfacial recombination, enhances efficiency and fill factor; post-deposition annealing improves crystallinity
Light-Emitting Devices (LEDs / Lasers)	ZnTe thin films or ZnTe-based quantum wells; doped/alloyed for emission tuning	Direct band gap, high radiative efficiency, tunable emission via Mn, Cu, or other dopants	Emission in visible and near-UV range; alloying/doping allows wavelength tuning; heterostructures improve quantum efficiency and lifetime
Optoelectronic Devices / Sensors	ZnTe heterojunctions with other II–VI semiconductors	High absorption coefficient, low resistivity after doping, compatibility with heterostructures	Used in photonic devices, sensors, and spintronic applications; Mn doping introduces localized states for spin-based devices

IX. CHALLENGES AND FUTURE PERSPECTIVES

ZnTe thin films have been extensively studied over the past several decades due to their unique optical and electronic properties, which make them promising candidates for a wide range of optoelectronic applications, including photodetectors, solar cells, and light-emitting devices. Despite significant advancements, several challenges continue to limit the performance, reproducibility, and commercial applicability of ZnTe-based

devices. Addressing these challenges is crucial to fully exploit the potential of ZnTe thin films in next-generation optoelectronic technologies. One of the primary challenges is achieving low-resistivity, high-mobility ZnTe films with controlled and reproducible p-type conductivity. Undoped ZnTe exhibits intrinsic p-type behavior due to zinc vacancies, but the carrier concentration and mobility are often insufficient for high-performance devices. Furthermore, self-compensation effects and the formation of deep-level defect states often hinder the activation of intentional dopants, making it difficult to achieve precise

control over electrical properties. Transition metal and Group V dopants can enhance conductivity and modify band structure, but excessive doping may introduce trap states, reduce carrier mobility, and degrade optical performance. Therefore, optimizing doping strategies and understanding defect formation mechanisms remain critical research areas. Another significant challenge lies in defect management and grain boundary control, particularly for polycrystalline ZnTe films deposited using chemical or low-temperature methods [22]. Grain boundaries serve as charge trapping centers, impeding carrier transport and contributing to recombination losses. Similarly, intrinsic point defects, secondary phases, and non-stoichiometry adversely affect carrier lifetime and photoconductivity. Advanced post-deposition treatments, such as thermal annealing in controlled atmospheres, chemical passivation, and surface modification, have been shown to improve crystallinity and reduce defect density. However, achieving uniform defect control across large-area films suitable for industrial-scale applications remains a major hurdle. Interface engineering is also a critical concern for ZnTe-based heterojunction devices. Efficient charge separation and transport in photodetectors and solar cells depend on precise alignment of energy bands at the ZnTe interface with other semiconductors such as CdS, ZnO, or CdTe. Poor interface quality can result in charge recombination, high series resistance, and reduced device efficiency. Therefore, future research must focus on novel heterojunction architectures, including nanostructured interfaces and graded compositions, to minimize interfacial defects and improve charge collection. Looking forward, the future of ZnTe thin films is likely to involve exploration of nanostructured morphologies, such as nanorods, nanowires, and quantum dots, which can enhance light absorption, carrier separation, and surface-to-volume ratios. Integration with flexible, transparent, and lightweight substrates is another promising avenue, enabling ZnTe-based devices for wearable and transparent optoelectronics. Furthermore, the development of hybrid deposition methods that combine the advantages of physical and chemical techniques may allow precise control over film composition, morphology, and defect density while maintaining scalability. Emerging applications, such as spintronic devices based on Mn-doped ZnTe, also highlight the potential of functional doping in expanding the scope of ZnTe beyond conventional optoelectronics. In conclusion, overcoming challenges related to doping, defect engineering, interface optimization, and scalable fabrication will be critical to unlock the full potential of ZnTe thin films. Continued research in these areas, coupled with innovative device architectures and nanostructured designs, is expected to drive the development of high-performance, next-generation optoelectronic and photonic devices based on ZnTe [23].

X. CONCLUSION

Zinc telluride (ZnTe) thin films represent a highly versatile and promising class of II–VI semiconductor materials with broad applicability in optoelectronic and photonic devices. Their direct band gap (~2.26 eV), strong absorption in the visible spectrum, and tunable electrical properties make them particularly suitable for

photodetectors, solar cells, light-emitting diodes, and emerging spintronic devices. Over the past decades, significant progress has been made in understanding the relationship between deposition methods, microstructure, and the resulting optical and electrical performance of ZnTe thin films. Advances in physical deposition techniques, including thermal and electron beam evaporation, sputtering, and molecular beam epitaxy, have enabled the growth of high-crystallinity films with precise control over thickness, composition, and interface quality. At the same time, chemical deposition methods, such as chemical bath deposition, electrodeposition, spray pyrolysis, and SILAR, have provided cost-effective, scalable alternatives suitable for large-area substrates, with post-deposition treatments improving crystallinity and optoelectronic performance. Both classes of deposition techniques have demonstrated their strengths, and hybrid approaches combining their advantages are likely to play a critical role in future ZnTe device fabrication. The tuning of electrical and optical properties through doping has further expanded the functional capabilities of ZnTe thin films. Transition metal dopants such as Mn, Cu, and Co have been shown to modify the band structure, enhance carrier concentration, and enable novel spintronic applications, while non-metal and Group V dopants such as nitrogen and phosphorus facilitate stable p-type conductivity. Nevertheless, challenges remain in achieving low-resistivity, high-mobility films, due to defect formation, self-compensation, and grain-boundary effects. Control over intrinsic defects, interface quality, and film microstructure continues to be essential for realizing the full potential of ZnTe-based devices. ZnTe thin films have demonstrated substantial promise in photodetectors, where heterojunction formation with CdS or ZnO enhances responsivity and reduces dark current, in solar cells, where ZnTe functions as a back contact or buffer layer in CdTe-based devices, and in light-emitting and optoelectronic devices, where doping and alloying enable emission tuning in the visible and near-UV regions. Looking forward, further research is expected to focus on nanostructured ZnTe, flexible and transparent substrates, and innovative heterojunction architectures to enable high-performance, next-generation devices. In conclusion, the combination of versatile deposition strategies, tunable doping, and microstructural engineering makes ZnTe thin films a compelling material for modern optoelectronic applications. Continued efforts in defect control, carrier mobility enhancement, and device integration will be key to unlocking new technological possibilities, establishing ZnTe thin films as a robust platform for high-performance optoelectronic and photonic devices.

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