Volume 11, Issue 1, January – 2026 International Journal of Innovative Science and Research Technology
ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jan1101

Cadmium Telluride (CdTe): A Comprehensive Review on Properties, Thin-Film Fabrication, and Applications

Ujjwal Prasad[1]; Pushp Raj Harsh[1]; S. R. Kumar[2]; K. Prasad[1]

[1]University Department of Physics, T.M. Bhagalpur University, Bhagalpur 812007, India.

[2]Department of Applied Science and Humanities,
National Institute of Advanced Manufacturing Technology, Hatia, Ranchi 834003, India

Publication Date: 2026/01/28

Abstract: Cadmium telluride (CdTe) is a II–VI compound semiconductor that has attracted significant scientific and technological interest due to its favorable optoelectronic properties, particularly its direct band gap, high absorption coefficient, and excellent electronic characteristics. CdTe possesses a direct band gap of approximately 1.45 eV at room temperature, which is close to the optimal band gap for solar energy conversion according to the Shockley–Queisser limit. This makes CdTe one of the most promising absorber materials for thin-film photovoltaic applications. Moreover, CdTe exhibits a very high absorption coefficient (greater than 10^5 cm^{-1}) in the visible spectral region, enabling the absorption of most incident solar radiation within a few micrometers of material thickness. These intrinsic properties allow the fabrication of efficient and cost-effective thin-film devices using relatively small amounts of material compared to conventional crystalline silicon technologies. Cadmium telluride (CdTe) is a II–VI compound semiconductor that has attracted significant attention due to its direct band gap, high absorption coefficient, and excellent optoelectronic properties. CdTe has been widely used in photovoltaic devices, photodetectors, radiation detectors, and other electronic and optoelectronic applications. This review article provides a comprehensive overview of CdTe, including its crystal structure, physical and chemical properties, fabrication techniques, device applications, challenges, and future research directions.

Keywords: *CdTe, Optoelectronic, Solar Cell, Photodetector.*

How to Cite: Ujjwal Prasad; Pushp Raj Harsh; S. R. Kumar; K. Prasad (2026) Cadmium Telluride (CdTe): A Comprehensive Review on Properties, Thin-Film Fabrication, and Applications. *International Journal of Innovative Science and Research Technology*, 11(1), 2033-2044. https://doi.org/10.38124/ijisrt/26jan1101

I. INTRODUCTION

Cadmium telluride (CdTe) is a II–VI compound semiconductor that has gained remarkable attention in the fields of materials science, electronics, and optoelectronics due to its outstanding physical, chemical, and optoelectronic properties. Over the past few decades, CdTe has emerged as one of the most promising semiconductor materials for thin-film photovoltaic devices, photodetectors, radiation detectors, and a wide range of optoelectronic applications. The increasing global demand for renewable energy sources, high-performance electronic devices, and advanced sensing technologies has further accelerated research on CdTe-based materials and devices. One of the most significant advantages of CdTe is its direct band gap of approximately 1.45 eV at room temperature, which is very close to the ideal band gap for solar energy conversion [1]. According to theoretical efficiency limits, semiconductors with band gaps between 1.1 and 1.6 eV are optimal for single-junction solar cells, and CdTe falls precisely within this range. The direct nature of the band gap enables strong light absorption and efficient electron–hole pair generation without the need for phonon-assisted transitions. As a result, CdTe can absorb more than 90% of incident solar radiation within a thickness of only a few micrometers, making it highly suitable for thin-film solar cell technology. This property allows the fabrication of lightweight, flexible, and cost-effective photovoltaic modules compared to conventional crystalline silicon solar cells, which require much thicker absorber layers. In addition to its favorable band gap, CdTe exhibits a very high absorption coefficient (greater than 10^5 cm^{-1}) in the visible region of the electromagnetic spectrum. This high absorption coefficient is attributed to its direct electronic transitions and strong interaction with photons. Consequently, CdTe thin films can be used to fabricate highly efficient optoelectronic devices with minimal material consumption. The optical properties of CdTe, such as refractive index, extinction coefficient, and photoluminescence characteristics, have been extensively studied to understand the role of intrinsic and extrinsic defects, excitonic effects, and recombination mechanisms. CdTe also possesses excellent electronic properties, including relatively high carrier mobility and suitable carrier lifetimes, which are essential for efficient charge transport in semiconductor devices [2]. The electron mobility in CdTe is typically higher than that of holes, which influences device design and performance optimization. Furthermore, CdTe can be doped to achieve either n-type or p-type conductivity, although achieving stable and controlled doping remains a challenge due to its complex defect chemistry. Native point defects, such as cadmium vacancies, tellurium vacancies, interstitials, and antisite defects, play a crucial role in determining the electrical behavior of CdTe. Understanding and controlling these defects through growth conditions, doping, and post-deposition treatments are key factors in improving device efficiency [3], [4]. The crystal structure of CdTe is another important aspect that influences its physical properties. Under ambient conditions, CdTe crystallizes in the zinc blende cubic structure, with tetrahedral coordination between cadmium and tellurium atoms. This structure results in strong covalent bonding with partial ionic character, which contributes to its semiconducting behavior. CdTe can also exhibit other polymorphic structures, such as wurtzite and rock-salt phases, under specific conditions of pressure and temperature. The microstructural properties, including grain size, grain boundaries, and crystallographic orientation, significantly affect the optical and electrical performance of CdTe thin films. For example, larger grain sizes and reduced grain boundary density are desirable for photovoltaic applications, as grain boundaries often act as recombination centers for charge carriers. A variety of fabrication techniques have been developed for the deposition of CdTe thin films and bulk materials. These techniques include close-spaced sublimation (CSS), chemical bath deposition (CBD), thermal evaporation, sputtering, electrodeposition, and molecular beam epitaxy (MBE). Each method has its own advantages and limitations in terms of film quality, deposition rate, scalability, and cost. CSS is widely used in industrial CdTe solar cell production due to its ability to produce high-quality polycrystalline films with large grain sizes. On the other hand, solution-based techniques such as CBD and electrodeposition are attractive for low-cost and large-area applications, particularly in developing regions. Post-deposition treatments, such as annealing in $CdCl_2$ atmosphere, are commonly employed to enhance grain growth, reduce defect density, and improve electrical properties. Characterization of CdTe materials is essential to understand their structural, optical, and electrical behavior. Structural characterization techniques, such as X-ray diffraction (XRD), are used to determine crystal structure, phase purity, lattice parameters, and crystallite size. Surface morphology and microstructural features are examined using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Optical properties, including band gap energy, absorption coefficient, and optical constants, are typically studied using UV–Visible spectroscopy and photoluminescence spectroscopy. Electrical properties, such as resistivity, carrier concentration, and mobility, are investigated using current–voltage measurements, Hall effect analysis, and impedance spectroscopy. These characterization techniques provide valuable insights into the relationship between processing conditions, microstructure, and device performance. CdTe has been extensively used in a wide range of device applications. In the field of photovoltaics, CdTe is one of the leading thin-film solar cell technologies, with laboratory efficiencies exceeding 22% and commercial module efficiencies above 19%. CdTe/CdS heterojunction solar cells are the most common device architecture, where CdS acts as the n-type window layer and CdTe serves as the p-type absorber layer [3]. The heterojunction interface plays a critical role in charge separation and collection. In addition to solar cells, CdTe is widely used in photodetectors due to its strong light absorption and fast response characteristics. CdTe-based photodetectors are used in optical communication systems, imaging devices, and environmental monitoring. Furthermore, CdTe is an important material for radiation detection applications. Due to its high atomic number and density, CdTe has a high stopping power for X-rays and gamma rays, making it suitable for medical imaging, security scanning, and nuclear radiation monitoring. CdTe and its alloys, such as CdZnTe and HgCdTe, are also used in infrared detectors and focal plane arrays for military, astronomical, and industrial applications [5]. These applications demonstrate the versatility and technological importance of CdTe as a multifunctional semiconductor material. Despite its many advantages, CdTe technology faces several challenges that must be addressed for widespread and sustainable deployment. One of the primary concerns is the toxicity of cadmium, which poses environmental and health risks. Strict regulations and proper handling procedures are required during material synthesis, device fabrication, and end-of-life recycling. Another challenge is the formation of low-resistance and stable back contacts in CdTe devices, which is difficult due to its high electron affinity and Fermi level pinning. Additionally, long-term stability and degradation under environmental conditions, such as moisture, temperature, and illumination, remain important research topics. Future research directions in CdTe technology include the development of nanostructured CdTe materials, such as quantum dots, nanowires, and nanoparticles, which exhibit unique size-dependent properties due to quantum confinement effects. CdTe quantum dots are being explored for applications in light-emitting diodes, bioimaging, and photodetectors. Another promising area is the integration of CdTe with emerging materials, such as perovskites and two-dimensional materials, to form tandem and hybrid devices with enhanced performance. CdTe-based tandem solar cells have the potential to surpass the efficiency limits of single-junction devices, while maintaining good stability and scalability. In conclusion, CdTe is a highly versatile and technologically significant semiconductor material with exceptional optoelectronic properties and a wide range of applications. Continued research on its fundamental properties, fabrication techniques, defect engineering, and device architectures is expected to further improve its performance and expand its application areas. With ongoing advancements in material science and device engineering, CdTe is poised to play a crucial role in future energy, sensing, and optoelectronic technologies [6], [7].

II. CRYSTAL STRUCTURE AND BASIC PROPERTIES OF CdTe

A. Crystal Structure

Cadmium telluride (CdTe) crystallizes in the zinc blende cubic structure under ambient conditions, belonging to the space group *F-43m*. In this structure, cadmium (Cd) and tellurium (Te) atoms are tetrahedrally coordinated, forming a highly symmetric face-centered cubic (FCC) lattice with a lattice constant of approximately a ≈ 6.48 Å. This tetrahedral coordination leads to strong covalent bonding with partial ionic character, which significantly influences the electronic band structure and optical properties of CdTe [8]. The crystalline nature and phase purity of CdTe thin films are commonly investigated using X-ray diffraction (XRD). Typical XRD patterns of polycrystalline CdTe films exhibit prominent diffraction peaks corresponding to the cubic zinc blende phase. The most intense diffraction peak is generally observed at the (111) plane, indicating a preferred orientation along this direction. Other characteristic peaks appear at (220) and (311) planes, confirming the polycrystalline cubic structure [9]. These peaks match well with standard JCPDS/ICDD data (PDF No. 15-0770), confirming the formation of single-phase CdTe without secondary phases. The lattice parameter (a) of cubic CdTe can be calculated using Bragg's law and the cubic lattice relation:

$$d_{hkl} = \frac{a}{\sqrt{h^2 k^2 l^2}}$$

where d_{hkl} is the interplanar spacing and (hkl) are Miller indices. Using the (111) diffraction peak, the lattice constant is typically found to be close to the reported bulk value, indicating good crystallinity.The crystallite size (D) of CdTe thin films is estimated using the Scherrer equation:

$$D = \frac{0.9\lambda}{\beta cos\theta}$$

where λ is the X-ray wavelength (Cu Kα = 1.5406 Å), β is the full width at half maximum (FWHM) of the diffraction peak, and θ is the Bragg angle. Typical crystallite sizes for CdTe thin films range from tens to hundreds of nanometers, depending on deposition conditions and post-annealing treatments. The microstrain (ε) in the lattice can be calculated using:

$$\varepsilon = \frac{\beta}{4tan\theta}$$

Microstrain arises due to lattice distortions, defects, and grain boundaries in the thin films.The dislocation density (δ), which represents the density of crystal imperfections, is determined using:

$$\delta = \frac{1}{D^2}$$

A lower dislocation density and microstrain indicate improved crystalline quality, which is crucial for enhancing charge transport and reducing recombination losses in CdTe-based optoelectronic devices.

B. Electronic Properties

Cadmium telluride (CdTe) is a direct band gap semiconductor with a band gap energy of approximately 1.45 eV at room temperature, which is very close to the optimum band gap required for high-efficiency single-junction solar cells. In a direct band gap semiconductor, the minimum of the conduction band and the maximum of the valence band occur at the same momentum (k) value in the Brillouin zone [6], [10]. This feature enables direct electronic transitions between the valence and conduction bands without the need for phonon assistance. As a result, CdTe exhibits strong optical absorption and efficient radiative recombination, making it highly suitable for optoelectronic applications such as solar cells, photodetectors, and light-emitting devices. The electronic band structure of CdTe is primarily governed by the hybridization of cadmium 5s and tellurium 5p orbitals, which form the conduction and valence bands, respectively. The high absorption coefficient of CdTe (greater than 10^5 cm^{-1} in the visible region) is a direct consequence of its direct band gap nature. This allows thin CdTe layers, typically a few micrometers thick, to absorb most of the incident solar radiation, significantly reducing material usage compared to indirect band gap semiconductors like silicon [11]. Carrier transport properties are crucial for determining the performance of semiconductor devices, and CdTe exhibits favorable carrier mobility values. The electron mobility in CdTe is typically around 1000 $cm^2/V \cdot s$, while the hole mobility is comparatively lower, around 100 $cm^2/V \cdot s$. This asymmetry in carrier mobility influences device design, as electrons generally move more efficiently than holes. The mobility values in CdTe depend strongly on factors such as crystal quality, defect density, grain boundaries, and doping concentration. In polycrystalline CdTe thin films, grain boundaries can act as scattering centers and recombination sites, reducing effective mobility and carrier lifetime. CdTe can exhibit both n-type and p-type conductivity, although achieving stable and controlled doping remains challenging.

Intrinsic CdTe tends to show p-type behavior due to the presence of cadmium vacancies, which act as acceptor defects. Conversely, tellurium vacancies and cadmium interstitials can act as donor defects, leading to n-type conductivity under certain growth conditions. Extrinsic doping using elements such as Cu, Ag, Cl, In, and Sb is commonly employed to tailor the electrical properties and improve device performance. For example, copper doping is widely used to enhance p-type conductivity and reduce contact resistance in CdTe solar cells. The carrier lifetime and recombination mechanisms in CdTe are also critical for optoelectronic applications. Radiative recombination, Auger recombination, and defect-assisted Shockley–Read–Hall (SRH) recombination processes determine the overall device efficiency. Reducing defect density through optimized growth conditions and post-deposition treatments, such as $CdCl_2$ annealing, significantly improves carrier lifetime and photovoltaic performance. Overall, the combination of an ideal band gap, high absorption coefficient, and favorable carrier mobility makes CdTe one of the most promising semiconductor materials for high-performance optoelectronic devices. Continued research on defect engineering, doping control, and interface optimization is essential to further enhance the electronic properties of CdTe-based devices [12].

C. Optical Properties

Cadmium telluride (CdTe) exhibits excellent optical properties that make it one of the most promising materials for optoelectronic and photovoltaic applications. One of the most important optical characteristics of CdTe is its strong absorption in the visible region, with an absorption coefficient typically exceeding 10^5 cm^{-1}. This exceptionally high absorption coefficient is primarily due to its direct band gap nature, which allows efficient electronic transitions between the valence and conduction bands without phonon assistance [5], [13], [14], [15]. As a result, CdTe thin films with thicknesses of only a few micrometers are sufficient to absorb most of the incident solar radiation, making it highly suitable for thin-film solar cell and photodetector applications. The optical band gap of CdTe is commonly determined using UV–Visible absorption spectroscopy and analyzed through the Tauc relation for direct band gap semiconductors:

$$(\alpha h\nu)^2 = A(h\nu - E_g)$$

where α is the absorption coefficient, hν is the photon energy, E_g is the optical band gap, and A is a constant. By extrapolating the linear portion of the plot, the band gap energy of CdTe is typically found to be around 1.45 eV, although slight variations may occur depending on film thickness, deposition technique, and doping concentration. Such variations are often attributed to quantum confinement effects, strain, and defect states in the material. The refractive index (n) of CdTe is another important optical parameter, typically ranging from 2.7 to 3.0 in the visible region. A high refractive index is beneficial for optical devices such as photonic and optoelectronic components, as it enhances light–matter interaction and optical confinement. The refractive index and extinction coefficient (k) are often derived from reflectance and transmittance measurements using optical models such as the Swanepoel method or ellipsometry. These parameters are crucial for designing optical coatings, waveguides, and multilayer solar cell structures. Photoluminescence (PL) spectroscopy is widely used to investigate the radiative recombination processes and defect states in CdTe. PL spectra of high-quality CdTe typically exhibit a strong near-band-edge emission corresponding to excitonic recombination, indicating good crystalline quality and low defect density. In addition to excitonic emission, defect-related luminescence bands are often observed, which are associated with intrinsic defects such as cadmium vacancies, tellurium vacancies, interstitials, and impurity states introduced during doping. These defect-related emissions provide valuable insights into the defect chemistry and recombination mechanisms in CdTe thin films. The optical properties of CdTe are strongly influenced by microstructural features such as grain size, crystallinity, surface roughness, and defect density. For instance, improved crystallinity and larger grain sizes generally result in sharper absorption edges and stronger PL emission, indicating reduced non-radiative recombination [13]. Post-deposition treatments, such as $CdCl_2$ annealing, are commonly used to enhance optical quality by promoting grain growth and reducing defect density. Overall, the strong visible light absorption, high refractive index, and characteristic photoluminescence behavior make CdTe an ideal material for solar cells, photodetectors, light-emitting devices, and other optoelectronic applications. Understanding and controlling the optical properties of CdTe through deposition parameters, doping, and post-treatment processes are essential for optimizing the performance of CdTe-based devices.

D. Electrical Properties

Cadmium telluride (CdTe) is a versatile semiconductor material whose electrical properties can be tailored through intrinsic defect control and extrinsic doping. CdTe can exhibit both n-type and p-type conductivity, depending on growth conditions, stoichiometry, and dopant incorporation. The electrical behavior of CdTe is strongly influenced by its defect chemistry, which plays a critical role in determining carrier concentration, mobility, resistivity, and recombination mechanisms [10], [16]. In intrinsic CdTe, native point defects such as vacancies, interstitials, and antisite defects are commonly present. Among these defects, cadmium vacancies act as acceptor-type defects and are primarily responsible for p-type conductivity in CdTe. These vacancies introduce acceptor levels near the valence band, facilitating hole generation. On the other hand, tellurium vacancies act as donor-type defects, contributing to n-type conductivity by introducing donor levels near the conduction band. Other defects such as cadmium interstitials and tellurium interstitials can also influence the electrical properties, although their formation energies are typically higher. The dominance of specific defects depends on the growth environment. Under Te-rich conditions, cadmium vacancies are more likely to form, leading to p-type CdTe, whereas Cd-rich conditions favor the formation of tellurium vacancies and n-type behavior. This sensitivity to stoichiometry makes defect control a crucial factor in optimizing CdTe-based devices. Extrinsic doping is widely employed to tailor the electrical properties of CdTe for specific applications. Dopants such as Cu, Ag, and Sb are commonly used to enhance p-type conductivity, while Cl, In, and Al are used as donor dopants to achieve n-type behavior. For instance, copper is widely used in CdTe solar cells to improve hole concentration and reduce back-contact resistance. However, excessive Cu diffusion can lead to long-term device degradation, highlighting the need for controlled doping strategies.The electrical conductivity (σ) of CdTe is governed by the carrier concentration (n or p) and mobility (μ), and can be expressed as:

$$\sigma = q(n\mu_n + p\mu_p)$$

where q is the electronic charge, n and p are electron and hole concentrations, and μ_n and μ_p are electron and hole mobilities, respectively. Typical resistivity values for CdTe thin films range from 10^{-2} to 10^{6} Ω·cm, depending on deposition technique and doping. Grain boundaries and defects in polycrystalline CdTe thin films significantly affect electrical transport. Grain boundaries can act as potential barriers and recombination centers, reducing carrier mobility and lifetime. Post-deposition treatments, such as $CdCl_2$ annealing, are commonly used to passivate grain boundaries, enhance grain growth, and improve electrical conductivity. Carrier recombination in CdTe occurs through radiative, Auger, and defect-assisted Shockley–Read–Hall (SRH) mechanisms. Minimizing defect-related recombination is essential for achieving high-efficiency optoelectronic devices. Therefore, defect engineering, controlled doping, and interface optimization are critical strategies for improving the electrical performance of CdTe-based devices. In summary, the electrical properties of CdTe are strongly governed by native defects, doping, and microstructural features. Understanding and controlling these factors are essential for optimizing CdTe thin films for high-performance photovoltaic, photodetector, and electronic applications [17], [18].

III. FABRICATION TECHNIQUES FOR CDTE THIN FILMS

CdTe thin films can be fabricated using various deposition techniques, each with its advantages and limitations.

A. Chemical Bath Deposition (CBD)

Chemical bath deposition (CBD) is a simple, low-cost, and low-temperature solution-based technique widely used for the deposition of semiconductor thin films, including CdTe. Owing to its scalability, minimal equipment requirements, and ability to coat large and complex substrates, CBD is considered one of the most attractive methods for fabricating CdTe thin films for optoelectronic and photovoltaic applications. In the CBD process, precursor solutions containing cadmium and tellurium sources are prepared in an aqueous or non-aqueous medium. Common cadmium precursors include cadmium acetate, cadmium chloride, or cadmium sulfate, while tellurium precursors are typically derived from tellurium dioxide (TeO_2), sodium tellurite, or organotellurium compounds. Complexing agents such as ammonia, ethylenediaminetetraacetic acid (EDTA), triethanolamine (TEA), or ethylene glycol are often added to control the release rate of Cd^{2+} ions and stabilize the solution. The controlled release of Cd^{2+} and Te^{2-} ions is crucial for achieving uniform nucleation and growth of CdTe on the substrate surface. The deposition mechanism in CBD generally involves heterogeneous nucleation on the substrate surface followed by ion-by-ion growth or cluster-by-cluster growth [6]. In heterogeneous nucleation, Cd^{2+} and Te^{2-} ions react at the substrate surface to form CdTe nuclei, which subsequently grow into a continuous thin film. The growth kinetics are influenced by bath temperature, pH, precursor concentration, deposition time, and the nature of the complexing agents. Typically, CBD of CdTe is carried out at temperatures between 60 °C and 90 °C, which makes it compatible with low-cost substrates such as glass, fluorine-doped tin oxide (FTO), and indium tin oxide (ITO). The pH of the chemical bath plays a critical role in determining the film quality and stoichiometry. Alkaline conditions are often preferred to facilitate the reduction of tellurium species and the formation of CdTe. Non-aqueous CBD using solvents such as ethylene glycol can further improve film uniformity and reduce oxidation of tellurium species. Deposition time controls the film thickness, which typically ranges from a few hundred nanometers to several micrometers, depending on application requirements. One of the key advantages of CBD is the ability to achieve large-area, uniform, and conformal coatings with relatively simple equipment. The technique is highly suitable for industrial-scale production due to its low energy consumption and material utilization efficiency. Additionally, CBD allows easy incorporation of dopants by adding dopant precursors directly into the bath, enabling tailoring of electrical and optical properties of CdTe thin films. However, CBD-grown CdTe films often exhibit small grain sizes and a high density of defects compared to films deposited by high-temperature vacuum techniques such as close-spaced sublimation (CSS) or sputtering. Therefore, post-deposition treatments, such as annealing in $CdCl_2$ atmosphere or inert gas, are commonly employed to enhance crystallinity, increase grain size, and improve electrical properties. In summary, chemical bath deposition is a versatile and cost-effective technique for fabricating CdTe thin films, particularly suitable for large-area and low-cost optoelectronic applications. Optimization of deposition parameters and post-treatment processes is essential to achieve high-quality CdTe films with improved structural, optical, and electrical properties [19].

B. Close-Spaced Sublimation (CSS)

Close-spaced sublimation (CSS) is a high-temperature vacuum deposition technique that is widely used for the fabrication of high-quality CdTe thin films, particularly in industrial CdTe solar cell production. CSS has become one of the most commercially successful deposition methods for CdTe absorber layers due to its high deposition rate, excellent film quality, and scalability for large-area modules. In the CSS process, CdTe source material (in the form of powder, pellets, or sintered targets) is placed in close proximity to the substrate, typically separated by a small gap ranging from a few millimeters to a few centimeters. The source and substrate are heated independently in a controlled environment, usually under vacuum or an inert gas atmosphere. At elevated temperatures (typically 500–650 °C), CdTe sublimates from the source and recondenses on the heated substrate, forming a thin film. The close spacing between the source and substrate ensures a high material flux and efficient mass transport, leading to rapid film growth [17]. One of the key advantages of CSS is its ability to produce highly crystalline CdTe films with large grain sizes, often on the order of several micrometers. Large grain sizes are highly desirable for photovoltaic applications because they reduce grain boundary density, which in turn minimizes charge carrier recombination and improves carrier transport. Compared to low-temperature techniques such as chemical bath deposition or electrodeposition, CSS-grown CdTe films generally exhibit superior crystallinity, lower defect density, and better electrical performance. The deposition parameters in CSS, including source temperature, substrate temperature, ambient pressure, gas composition, and deposition time, play a crucial role in determining the microstructural and optoelectronic properties of CdTe films [20]. Higher substrate temperatures typically promote grain growth and improved crystallinity, while the ambient pressure and gas composition (e.g., inert gases such as argon or nitrogen) influence the transport of sublimated species and film stoichiometry. Deposition rates in CSS are relatively high, making it suitable for industrial-scale production. CSS is particularly attractive for commercial CdTe solar cell manufacturing, as it enables the deposition of thick CdTe absorber layers (typically 2–8 μm) required for efficient light absorption. The technique is compatible with large-area substrates and roll-to-roll processing, making it cost-effective for mass production. Many commercial CdTe photovoltaic modules are fabricated using CSS due to its high throughput and reliability. However, CSS also has certain limitations. The high processing temperature can limit the choice of substrates and increase energy consumption. Additionally, precise control of stoichiometry and uniformity across very large substrates can be challenging and requires sophisticated process control. Post-deposition treatments, such as $CdCl_2$ annealing, are often applied to further enhance grain growth, passivate defects, and improve device performance. In summary, close-spaced sublimation is a mature and industrially proven technique for depositing high-quality CdTe thin films. Its ability to produce large-grained, uniform, and highly crystalline films makes it one of the most important deposition methods for CdTe-based solar cells and optoelectronic devices. Continued optimization of CSS parameters and integration with advanced device architectures are expected to further enhance the performance and scalability of CdTe technologies [2], [12], [21].

C. Thermal Evaporation

Thermal evaporation is a widely used physical vapor deposition (PVD) technique for the fabrication of CdTe thin films, particularly in laboratory-scale research and optoelectronic device development. In this method, CdTe powder or pellets are heated in a high-vacuum environment until they evaporate and subsequently condense on a cooled substrate, forming a thin film. Thermal evaporation is favored for its simplicity, high purity of deposited films, and precise control over deposition parameters. In a typical thermal evaporation system, CdTe source material is placed in a resistively heated boat or crucible made of materials such as tungsten, molybdenum, or tantalum. The evaporation chamber is evacuated to high vacuum levels (typically 10^{-5}–10^{-6} Torr) to minimize contamination and collisions between evaporated atoms and residual gas molecules. When the source is heated, CdTe molecules or constituent Cd and Te species evaporate and travel in a line-of-sight trajectory toward the substrate, where they nucleate and grow into a thin film. One of the major advantages of thermal evaporation is its excellent control over film thickness and deposition rate. The thickness can be precisely monitored using a quartz crystal microbalance (QCM), allowing deposition of films ranging from a few nanometers to several micrometers. This makes thermal evaporation highly suitable for fabricating multilayer structures such as CdTe/CdS heterojunctions, metal contacts, and buffer layers in optoelectronic devices [6]. The film composition and stoichiometry can also be controlled by adjusting the evaporation rate, substrate temperature, and source material purity. However, CdTe has a tendency to dissociate during evaporation due to the different vapor pressures of Cd and Te, which can lead to non-stoichiometric films. To overcome this issue, techniques such as co-evaporation of Cd and Te from separate sources or post-deposition annealing in Cd or Te-rich environments are often employed to restore stoichiometry. Substrate temperature plays a critical role in determining the microstructural and optoelectronic properties of thermally evaporated CdTe films. At low substrate temperatures, films tend to be amorphous or poorly crystalline with small grain sizes. Increasing the substrate temperature promotes surface diffusion of adatoms, leading to improved crystallinity, larger grain sizes, and reduced defect density. Typically, substrate temperatures between 200 °C and 400 °C are used to achieve polycrystalline CdTe films with good structural quality. Thermally evaporated CdTe films are widely used in photovoltaic and photodetector applications due to their uniform thickness, smooth surface morphology, and compatibility with various substrates such as glass, fluorine-doped tin oxide (FTO), and indium tin oxide (ITO). The method is also suitable for depositing doped CdTe films by adding dopant materials (e.g., Cu, Sb, or In) to the evaporation source. Despite its advantages, thermal evaporation has some limitations. The requirement for high vacuum systems increases equipment cost, and maintaining stoichiometric control can be challenging due to differential evaporation rates of Cd and Te. Additionally, film uniformity over very large areas can be difficult to achieve without sophisticated substrate rotation and process control. In summary, thermal evaporation is a versatile and well-established technique for depositing CdTe thin films with controlled thickness and composition. Its simplicity, high purity, and compatibility with multilayer device fabrication make it an important deposition method for research and development of CdTe-based optoelectronic devices [22].

D. Sputtering

Sputtering is a widely used physical vapor deposition (PVD) technique for depositing high-quality CdTe thin films with excellent adhesion, uniformity, and controllable composition. Both radio-frequency (RF) sputtering and direct current (DC) sputtering are commonly employed for CdTe thin film growth in research and industrial applications. Compared to solution-based techniques, sputtering offers better control over film thickness, stoichiometry, and doping, making it highly suitable for fabricating optoelectronic and photovoltaic devices. In the sputtering process, a CdTe target (either stoichiometric CdTe or composite targets containing dopants) is bombarded by energetic ions, typically argon (Ar^+) ions, generated in a plasma. The ion bombardment ejects Cd and Te atoms or clusters from the target surface, which then travel toward the substrate and condense to form a thin film. In DC sputtering, a constant voltage is applied between the target and substrate, whereas RF sputtering is used for insulating or semiconducting targets like CdTe to sustain a stable plasma and prevent charge buildup on the target surface. One of the key advantages of sputtering is the excellent control over film composition and stoichiometry. By using high-purity CdTe targets and controlling the sputtering power, gas pressure, and substrate temperature, highly uniform and reproducible films can be achieved. Reactive sputtering can also be employed, where additional gases such as hydrogen or nitrogen are introduced to modify film properties. Furthermore, doping can be precisely controlled by using doped targets or co-sputtering from multiple targets, enabling the incorporation of elements such as Cu, Sb, In, or Cl to tailor the electrical and optical properties of CdTe films. The substrate temperature during sputtering plays a critical role in determining the crystallinity and microstructure of CdTe films. At low substrate temperatures, sputtered CdTe films may be amorphous or nanocrystalline with small grain sizes. Increasing the substrate temperature enhances surface diffusion of adatoms, leading to improved crystallinity, larger grain sizes, and reduced defect density. Typical substrate temperatures range from room temperature to 400 °C, depending on the desired film properties and substrate compatibility. Sputtering offers several advantages for CdTe thin film deposition. It provides strong film adhesion to substrates such as glass, FTO, ITO, silicon, and flexible polymers. The technique is highly scalable and compatible with large-area deposition, making it suitable for industrial manufacturing of CdTe solar modules. Additionally, sputtering allows precise control over film thickness, which can be monitored using deposition rate calibration and in-situ thickness sensors. However, sputtering also has some limitations. The deposition rate is generally lower compared to techniques like close-spaced sublimation, and the equipment cost is higher due to the need for vacuum systems and plasma generation units. Additionally, sputtered CdTe films may require post-deposition annealing, such as $CdCl_2$ treatment, to improve grain growth, reduce defects, and enhance electrical performance. In photovoltaic applications, sputtered CdTe is often used as an absorber layer in CdTe/CdS heterojunction solar cells. Sputtering is also employed for depositing buffer layers, window layers, and back-contact layers, making it a versatile technique for complete device fabrication. The ability to deposit multilayer structures with high precision makes sputtering particularly attractive for research on advanced device architectures. In summary, RF and DC sputtering are powerful and versatile techniques for depositing CdTe thin films with controlled thickness, composition, and doping. Their excellent uniformity, adhesion, and scalability make them essential methods for the development of high-performance CdTe-based optoelectronic and photovoltaic devices [6].

E. Electrochemical Deposition

Electrochemical deposition, also known as electrodeposition, is a simple, low-cost, and scalable technique for fabricating CdTe thin films. In this method, CdTe films are deposited onto conductive substrates through an electrochemical reaction occurring at the electrode–electrolyte interface. Typically, substrates such as fluorine-doped tin oxide (FTO), indium tin oxide (ITO), or metal-coated glass are used as the working electrode, while a counter electrode (such as platinum or graphite) and a reference electrode (Ag/AgCl or saturated calomel electrode) complete the electrochemical cell. The electrolyte solution generally contains cadmium and tellurium precursor ions, such as Cd^{2+} and TeO_3^{2-}, dissolved in an aqueous acidic or alkaline medium. By applying an appropriate cathodic potential or current, Cd^{2+} and Te species are simultaneously reduced and deposited on the substrate, forming a CdTe compound film. The deposition parameters—including applied voltage/current density, bath composition, temperature, pH, and deposition time—play a crucial role in controlling film thickness, stoichiometry, crystallinity, and microstructure. One of the major advantages of electrodeposition is its low processing temperature, typically below 100 °C, which makes it compatible with flexible and low-cost substrates. Additionally, the technique allows large-area and uniform film deposition, making it highly attractive for industrial-scale photovoltaic manufacturing. The method also offers excellent control over doping and composition by simply adjusting the electrolyte chemistry or deposition conditions. However, electrodeposited CdTe films often require post-deposition annealing or $CdCl_2$ treatment to improve crystallinity, grain size, and electrical properties. Despite this, electrodeposition remains one of the most promising and economical methods for producing CdTe thin films for solar cells and optoelectronic devices due to its simplicity, scalability, and cost-effectiveness [16].

IV. CDTE-BASED DEVICE APPLICATIONS

A. CdTe Solar Cells

Cadmium telluride (CdTe) is one of the most promising and widely used absorber materials for thin-film solar cells due to its near-ideal band gap (~1.45 eV), high absorption coefficient ($>10^5$ cm^{-1}), and excellent radiation and thermal stability. These properties enable CdTe to absorb most of the solar spectrum with a relatively thin absorber layer (1–3 µm), making it highly suitable for cost-effective photovoltaic devices. Over the past decades, CdTe solar cell technology has matured significantly, with laboratory-scale power conversion efficiencies exceeding 22%, and commercial module efficiencies surpassing 20%, positioning CdTe as a strong competitor to crystalline silicon photovoltaics [7], [7], [19]. A typical CdTe solar cell device structure consists of a glass/FTO (or ITO)/CdS/CdTe/back contact configuration. In this heterojunction architecture, CdTe acts as the p-type absorber layer, while cadmium sulfide (CdS) serves as the n-type window layer. The CdS layer is usually deposited with a thickness of 50–150 nm to allow sufficient light transmission while forming an efficient p–n junction with CdTe. The heterojunction between CdTe and CdS facilitates charge separation and carrier collection, which is critical for efficient photovoltaic operation. The back contact plays a crucial role in CdTe solar cell performance. Due to the high electron affinity and low work function alignment of CdTe, forming an ohmic contact is challenging. Therefore, metals such as gold (Au), copper (Cu), silver (Ag), or carbon-based contacts are commonly employed, often in combination with interfacial layers like ZnTe:Cu or graphite to improve contact properties. Copper is frequently used as a dopant or interfacial layer to enhance p-type conductivity and reduce contact resistance, although excessive Cu diffusion can lead to long-term device instability. One of the key processing steps in CdTe solar cell fabrication is $CdCl_2$ treatment, which significantly improves grain growth, crystallinity, and defect passivation in CdTe films. This post-deposition annealing process enhances carrier lifetime, reduces recombination centers, and improves junction quality, leading to higher efficiency and device stability. CdTe solar cells offer several advantages, including low material usage, low manufacturing cost, scalability for large-area modules, and high energy yield in hot and low-light conditions. Additionally, CdTe technology has a lower carbon footprint and energy payback time compared to conventional silicon-based photovoltaics. However, concerns related to cadmium toxicity and tellurium scarcity have motivated ongoing research into recycling strategies, alternative contact materials, and improved device architectures [23]. Overall, CdTe-based photovoltaic devices remain one of the most commercially successful thin-film technologies, with continuous research focused on improving efficiency, stability, and environmental sustainability for next-generation solar energy applications [11], [15], [21].

B. Photodetectors

Cadmium telluride (CdTe) is a versatile semiconductor material widely employed in photodetector applications due to its direct band gap of ~1.45 eV, high absorption coefficient ($>10^5$ cm^{-1}), and excellent charge carrier transport properties. The combination of these properties enables efficient light absorption, fast carrier generation, and rapid photogenerated current response, making CdTe an ideal candidate for high-performance photodetectors operating in the visible to near-infrared spectral range. CdTe thin films deposited on conductive substrates, such as glass/FTO or glass/ITO, are commonly used as the active layer in photodetectors. The high absorption coefficient of CdTe allows even thin films (1–3 µm) to absorb most incident photons, generating electron–hole pairs efficiently. Upon illumination, these carriers are separated under an applied bias, producing a photocurrent proportional to the incident light intensity. The responsivity (R), defined as the ratio of photocurrent to incident optical power, is a critical figure of merit for photodetectors and typically reaches high values in CdTe thin films due to low recombination losses and favorable carrier mobilities. The response time, which is the time required for the photocurrent to rise or decay to a certain percentage of its maximum value, is also fast in CdTe devices because of high carrier mobility and low trap-assisted recombination [2].

Heterojunction devices using CdTe as the absorber layer and CdS as the window layer have gained significant attention for photodetection applications. The CdS layer, being a wide-bandgap (≈2.4 eV) n-type semiconductor, allows most visible light to pass through while forming a p–n junction with p-type CdTe. This junction facilitates efficient separation of photogenerated carriers and reduces dark current, thereby enhancing photoresponsivity and signal-to-noise ratio (SNR). The built-in electric field at the heterojunction interface accelerates charge separation and transport, resulting in fast response times, often in the millisecond to microsecond range, depending on device architecture and fabrication quality [9], [20], [24], [25].

The key performance metrics of CdTe-based photodetectors include *photocurrent (Iph), dark current (Id), responsivity (R), detectivity (D*), linear dynamic range (LDR), and response time (τ). Low dark current is crucial for high detectivity, and it can be minimized by optimizing film stoichiometry, improving crystallinity, and using passivation layers. Post-deposition treatments such as annealing or chemical passivation further enhance carrier mobility, reduce trap states, and improve device stability.

- *Advantages and Applications*

CdTe and CdTe/CdS photodetectors offer several advantages:

- High optical absorption and efficient photon-to-electron conversion
- Low-cost fabrication using techniques such as chemical bath deposition (CBD), sputtering, and thermal evaporation
- Compatibility with flexible and large-area substrates
- Fast response suitable for optical communication, imaging, and radiation detection

These features have enabled CdTe-based photodetectors to be used in visible light detection, solar-blind detectors, X-ray and gamma-ray detection, and imaging devices. Their robustness, stability, and tunable properties through doping and heterojunction engineering make them ideal for advanced optoelectronic applications.

C. Other Applications

Beyond photovoltaics and photodetectors, cadmium telluride (CdTe) is a versatile semiconductor material that finds applications in a variety of optoelectronic, thermoelectric, and infrared (IR) technologies due to its direct band gap, high absorption coefficient, and favorable electronic and thermal properties.

D. Light-Emitting Devices

CdTe is employed in light-emitting diodes (LEDs) and electroluminescent devices because of its ability to efficiently emit photons upon electron–hole recombination. The direct band gap of ~1.45 eV corresponds to emission in the near-infrared (NIR) and red regions of the spectrum, which is useful for optical communication, infrared signaling, and display technologies. CdTe thin films or nanocrystals can be incorporated into electroluminescent layers, where efficient radiative recombination occurs, providing bright and tunable emission. Furthermore, CdTe quantum dots exhibit size-dependent optical properties due to the quantum confinement effect, enabling precise control of emission wavelength for LEDs and display applications [5].

E. Thermoelectric Devices

CdTe also exhibits thermoelectric properties, allowing it to convert heat into electricity through the Seebeck effect. Its relatively high carrier mobility, moderate electrical conductivity, and low thermal conductivity make CdTe suitable for low- to medium-temperature thermoelectric applications. Thin-film CdTe can be integrated into thermoelectric generators for waste heat recovery in industrial processes or microelectronic devices. Doping and nanostructuring can further enhance the thermoelectric figure of merit (ZT) by improving carrier concentration and reducing phonon-mediated thermal conductivity, thereby increasing energy conversion efficiency [17].

F. Infrared Optics and Radiation Detection

CdTe is an excellent material for infrared optics and radiation detection due to its wide band gap, high atomic number, and density. CdTe and CdTe-based alloys, such as CdZnTe (CZT), are widely used in X-ray and gamma-ray detectors, including medical imaging, non-destructive testing, and security scanning systems. The high atomic number of Cd ($Z = 48$) and Te ($Z = 52$) enables efficient absorption of high-energy photons, while the wide band gap (~1.45 eV) ensures low thermal noise and stable operation at room temperature. Additionally, CdTe is transparent to mid-infrared wavelengths (2–20 µm), making it suitable for IR lenses, windows, and optical components in thermal imaging and spectroscopy. Ongoing research explores the use of CdTe in photocatalysis, spintronic devices, and nanophotonics. For example, CdTe nanoparticles have shown potential in photocatalytic water splitting and environmental pollutant degradation, leveraging their high absorption in the visible spectrum. CdTe nanostructures are also being investigated for plasmonic and quantum optical applications, where their size-dependent optical and electronic properties can be exploited for advanced photonic devices [5].

V. CHALLENGES AND LIMITATIONS

Cadmium telluride (CdTe) is a widely used semiconductor material in thin-film photovoltaics, photodetectors, and optoelectronic devices due to its near-ideal band gap, high absorption coefficient, and excellent charge transport properties. Despite these advantages, CdTe faces several technological and environmental challenges that limit its widespread adoption and long-term performance. Addressing these issues is critical for the sustainable and efficient use of CdTe-based devices.

A. Toxicity of Cadmium

One of the primary concerns associated with CdTe is the toxicity of cadmium, which is classified as a heavy metal with significant environmental and health risks. Cadmium exposure can lead to kidney damage, bone fragility, and carcinogenic effects if not properly managed. Although the cadmium in CdTe is chemically bound in a stable crystalline lattice, there is still a risk of release during manufacturing, recycling, or disposal. Consequently, stringent regulations govern the handling, processing, and disposal of CdTe materials. Research efforts are ongoing to develop safer encapsulation methods, recycling strategies for end-of-life modules, and alternative non-toxic semiconductor materials that can replicate CdTe's favorable optoelectronic properties [26].

B. Device Stability and Degradation

CdTe thin films can suffer from stability and degradation issues under operational conditions. Exposure to moisture, oxygen, UV radiation, and thermal cycling can lead to oxidation, defect formation, and interface degradation. For instance, moisture ingress can cause the formation of $Cd(OH)_2$ or Te oxides, which deteriorate the optoelectronic properties of the absorber layer. Furthermore, polycrystalline CdTe films may contain grain boundaries and defect sites that act as recombination centers, reducing carrier lifetime and device efficiency over time. Advanced encapsulation techniques, surface passivation, and controlled doping are actively being explored to mitigate these stability issues and improve the operational lifetime of CdTe devices [25].

C. Challenges in Back Contact Formation

Forming a stable and low-resistance back contact on p-type CdTe is a major technical challenge. CdTe's high electron affinity and wide band gap make it difficult to form an ohmic contact with conventional metals, leading to Schottky barriers that reduce fill factor and overall device efficiency. Metals such as gold (Au), silver (Ag), and copper (Cu) are commonly used, often with interfacial layers or doping strategies (e.g., ZnTe:Cu) to enhance hole injection and reduce contact resistance. However, Cu-based contacts can diffuse into the CdTe layer over time, causing instability [25]. Research is focused on developing alternative contact materials, graded junctions, and nanostructured interfacial layers to achieve both high efficiency and long-term stability [6].

D. Material Scarcity and Cost

Although CdTe modules are cost-effective in terms of energy payback, tellurium is a relatively rare element, and large-scale deployment of CdTe technology is limited by the global supply of Te. This scarcity motivates research into Te-free alternatives or the use of Te in combination with other II–VI compounds to reduce dependency on critical elements. Efficient recycling and recovery processes for CdTe modules are also being developed to address long-term material sustainability [6].

E. Performance Limitations at High Temperatures

CdTe devices can experience performance drops under high operating temperatures due to increased carrier recombination, thermal expansion mismatch with substrates, and degradation of interfaces. Optimizing the thermal management of devices through module design, encapsulation, and heat-dissipating materials is essential to maintain stable performance in real-world conditions [11].

VI. FUTURE PERSPECTIVES

Cadmium telluride (CdTe) has established itself as one of the most commercially successful thin-film semiconductors for photovoltaics and optoelectronic applications. With its near-ideal band gap (~1.45 eV), high absorption coefficient, and robust optoelectronic properties, CdTe-based devices have demonstrated power conversion efficiencies exceeding 22% in laboratory settings. Despite this success, continuous research is essential to address existing challenges and to unlock the full potential of CdTe in next-generation devices. The future perspectives of CdTe revolve around enhancing efficiency, environmental sustainability, flexibility, nanostructuring, and novel device architectures [27].

A. Improving Efficiency

While commercial CdTe solar modules typically operate at 18–21% efficiency, there remains room for improvement through optimization of material properties and device architecture. Future research is expected to focus on defect passivation, grain boundary engineering, and interface optimization. For example, reducing trap-assisted recombination at grain boundaries and at the CdS/CdTe interface can significantly enhance open-circuit voltage (Voc) and fill factor (FF). Advanced post-deposition treatments, such as controlled $CdCl_2$ annealing, halide-based passivation, and alkali-metal doping (Na, K), are being explored to improve crystallinity, reduce defects, and enhance carrier lifetime. Additionally, optimization of back-contact materials and the use of buffer layers can further reduce series resistance and enhance overall device performance.

B. Reducing Toxicity and Environmental Impact

Cadmium is a toxic heavy metal, which poses environmental and health concerns during manufacturing, deployment, and end-of-life disposal. Future research is focusing on environmentally safe fabrication, encapsulation, and recycling strategies. Development of closed-loop recycling processes for CdTe modules can recover cadmium and tellurium, minimizing environmental hazards and reducing material costs. Furthermore, studies are exploring non-toxic alternative materials or alloying strategies (e.g., CdSeTe, ZnTe, or quaternary II–VI compounds) that retain the excellent optoelectronic properties of CdTe while mitigating toxicity concerns.

C. Flexible and Lightweight Devices

The global demand for lightweight, flexible, and portable photovoltaics is driving research toward flexible CdTe thin films on polymer or metal foil substrates. Achieving high-quality, mechanically stable CdTe layers on flexible substrates requires low-temperature deposition techniques such as chemical bath deposition (CBD), electrodeposition, or sputtering, combined with optimized annealing protocols. Flexible CdTe devices have potential applications in building-integrated photovoltaics (BIPV), wearable electronics, and portable power systems, expanding the deployment scenarios beyond rigid glass-based modules.

D. Nanostructured CdTe

Nanostructuring represents a promising approach to enhance the performance of CdTe devices. Techniques such as CdTe nanowires, quantum dots, and nanorods can exploit quantum confinement effects, leading to tunable band gaps, enhanced light absorption, and improved carrier dynamics. CdTe quantum dots can be integrated into LEDs, photodetectors, and tandem solar cells to achieve broad spectral absorption, higher responsivity, and tunable emission properties. Nanostructured CdTe can also reduce recombination losses and improve charge extraction in photovoltaic devices, offering pathways to ultra-thin and high-efficiency solar cells.

E. Integration with Perovskites and Tandem Architectures

A major direction in photovoltaic research involves tandem and multi-junction solar cells. CdTe, with its optimal band gap, is well-suited for tandem configurations with perovskites, silicon, or other wide-bandgap absorbers. Perovskite/CdTe tandem solar cells can exploit complementary absorption spectra, where the perovskite top cell absorbs high-energy photons and CdTe absorbs lower-energy photons. This approach can theoretically surpass the Shockley–Queisser limit of single-junction cells, potentially achieving efficiencies above 30%. Ongoing research focuses on optimizing interfaces, reducing interlayer recombination, and ensuring thermal and chemical compatibility between layers.

F. Advanced Optoelectronic Applications

Beyond photovoltaics, future research aims to leverage CdTe in next-generation optoelectronic devices, including high-speed photodetectors, light-emitting devices, and radiation sensors. Enhancing carrier mobility, reducing defects, and engineering heterojunction interfaces will enable faster response times, higher photoresponsivity, and lower noise in photodetectors. Similarly, advances in nanostructured CdTe and heterostructures can expand applications in quantum photonics, spintronics, and infrared imaging, opening new technological frontiers.

VII. CONCLUSION

Cadmium telluride (CdTe) has firmly established itself as one of the most significant II–VI semiconductor materials in the fields of optoelectronics and photovoltaics. Its direct band gap of ~1.45 eV, high absorption coefficient, and excellent electronic properties enable efficient photon absorption and charge carrier generation, making CdTe particularly suitable for thin-film solar cells, photodetectors, and radiation detection systems. The material's ability to absorb a broad spectrum of visible light allows for thin absorber layers in solar cells, reducing material usage while maintaining high conversion efficiency. Similarly, its fast carrier response and low recombination losses make CdTe an ideal choice for photodetector and X-ray/gamma-ray detection applications. Over the past several decades, considerable research efforts have been dedicated to understanding and optimizing CdTe at multiple levels. Studies on crystal growth mechanisms, structural properties, defect formation, and doping behavior have provided valuable insights into improving the material's optoelectronic performance. Advanced characterization techniques, including X-ray diffraction (XRD), scanning electron microscopy (SEM), photoluminescence (PL), and current–voltage (I–V) measurements, have enabled a thorough understanding of the relationship between film microstructure and device performance. Furthermore, significant progress has been made in thin-film deposition techniques, such as chemical bath deposition (CBD), close-spaced sublimation (CSS), thermal evaporation, sputtering, and electrodeposition, which have allowed controlled growth of high-quality CdTe films suitable for diverse applications. Despite these achievements, several critical challenges remain in the broader adoption and long-term reliability of CdTe-based devices. The toxicity of cadmium necessitates careful handling, encapsulation, and recycling to mitigate environmental and health risks. Stability under operational conditions, particularly in terms of moisture, thermal cycling, and interface degradation, continues to be a limiting factor, requiring advanced passivation, annealing, and encapsulation strategies. In addition, interface engineering and back contact formation remain complex, as achieving low-resistance, chemically stable contacts is essential for high-efficiency devices. These challenges drive ongoing research in alternative contact materials, heterostructure design, and nanostructuring approaches to enhance carrier extraction and device performance. Looking forward, the future of CdTe technology lies in integrating advanced materials processing, nanostructured designs, and hybrid architectures. Nanostructured CdTe, including quantum dots, nanorods, and nanowires, offers the potential for tunable band gaps, enhanced light absorption, and improved carrier dynamics. Integration of CdTe with other semiconductors, such as perovskites in tandem solar cells, presents opportunities to surpass conventional single-junction efficiency limits. Additionally, research on flexible and lightweight CdTe devices expands the applicability to portable and building-integrated photovoltaics, as well as wearable optoelectronics. Optimizing doping strategies, interface engineering, and defect passivation will continue to play a central role in improving the efficiency, stability, and scalability of CdTe-based systems. In conclusion, CdTe remains a versatile and technologically important semiconductor, with significant potential to address the global need for efficient, low-cost, and scalable optoelectronic and photovoltaic solutions. Continued interdisciplinary research spanning materials science, device engineering, and sustainable processing is essential to overcome existing limitations and to realize the next generation of high-performance CdTe-based devices for energy conversion, sensing, and advanced optoelectronic applications.

REFERENCES

[1]. A. N. Tiwari, G. Khrypunov, F. Kurdzesau, D. L. Bätzner, A. Romeo, and H. Zogg, "CdTe solar cell in a novel configuration," Prog. Photovolt. Res. Appl., vol. 12, no. 1, pp. 33–38, Jan. 2004, doi: 10.1002/pip.525.
[2]. L. Kranz, S. Buecheler, and A. N. Tiwari, "Technological status of CdTe photovoltaics," Sol. Energy Mater. Sol. Cells, vol. 119, pp. 278–280, Dec. 2013, doi: 10.1016/j.solmat.2013.08.028.

[3]. C. Ferekides and J. Britt, “CdTe solar cells with efficiencies over 15%,” Sol. Energy Mater. Sol. Cells, vol. 35, pp. 255–262, Sep. 1994, doi: 10.1016/0927-0248(94)90148-1.

[4]. C. S. Ferekides et al., “High efficiency CSS CdTe solar cells,” Thin Solid Films, vol. 361–362, pp. 520–526, Feb. 2000, doi: 10.1016/S0040-6090(99)00824-X.

[5]. R. O. Bell, “Review of optical applications of CdTe,” Rev. Phys. Appliquée, vol. 12, no. 2, pp. 391–399, 1977, doi: 10.1051/rphysap:01977001202039100.

[6]. M. A. Scarpulla et al., “CdTe-based thin film photovoltaics: Recent advances, current challenges and future prospects,” Sol. Energy Mater. Sol. Cells, vol. 255, p. 112289, Jun. 2023, doi: 10.1016/j.solmat.2023.112289.

[7]. X. Mathew, J. P. Enriquez, A. Romeo, and A. N. Tiwari, “CdTe/CdS solar cells on flexible substrates,” Sol. Energy, vol. 77, no. 6, pp. 831–838, Dec. 2004, doi: 10.1016/j.solener.2004.06.020.

[8]. V. I. Kozlovsky, A. B. Krysa, Yu. V. Korostelin, and Yu. G. Sadofyev, “MBE growth and characterization of ZnTe epilayers and ZnCdTe/ZnTe structures on GaAs(100) and ZnTe(100) substrates,” J. Cryst. Growth, vol. 214–215, pp. 35–39, Jun. 2000, doi: 10.1016/S0022-0248(00)00054-3.

[9]. K. Durose, P. R. Edwards, and D. P. Halliday, “Materials aspects of CdTe/CdS solar cells,” J. Cryst. Growth, vol. 197, no. 3, pp. 733–742, Feb. 1999, doi: 10.1016/S0022-0248(98)00962-2.

[10]. B. Segall, M. R. Lorenz, and R. E. Halsted, “Electrical Properties of n -Type CdTe,” Phys. Rev., vol. 129, no. 6, pp. 2471–2481, Mar. 1963, doi: 10.1103/PhysRev.129.2471.

[11]. M. Gloeckler, I. Sankin, and Z. Zhao, “CdTe Solar Cells at the Threshold to 20% Efficiency,” IEEE J. Photovolt., vol. 3, no. 4, pp. 1389–1393, Oct. 2013, doi: 10.1109/JPHOTOV.2013.2278661.

[12]. R. W. Birkmire and B. E. McCandless, “CdTe thin film technology: Leading thin film PV into the future,” Curr. Opin. Solid State Mater. Sci., vol. 14, no. 6, pp. 139–142, Dec. 2010, doi: 10.1016/j.cossms.2010.08.002.

[13]. K. Sato and S. Adachi, “Optical properties of ZnTe,” J. Appl. Phys., vol. 73, no. 2, pp. 926–931, Jan. 1993, doi: 10.1063/1.353305.

[14]. S. Adachi, T. Kimura, and N. Suzuki, “Optical properties of CdTe: Experiment and modeling,” J. Appl. Phys., vol. 74, no. 5, pp. 3435–3441, Sep. 1993, doi: 10.1063/1.354543.

[15]. B. E. McCandless and K. D. Dobson, “Processing options for CdTe thin film solar cells,” Sol. Energy, vol. 77, no. 6, pp. 839–856, Dec. 2004, doi: 10.1016/j.solener.2004.04.012.

[16]. A. E. Rakhshani, “Electrodeposited CdTe—optical properties,” J. Appl. Phys., vol. 81, no. 12, pp. 7988–7993, Jun. 1997, doi: 10.1063/1.365402.

[17]. A. Bosio, N. Romeo, S. Mazzamuto, and V. Canevari, “Polycrystalline CdTe thin films for photovoltaic applications,” Prog. Cryst. Growth Charact. Mater., vol. 52, no. 4, pp. 247–279, Dec. 2006, doi: 10.1016/j.pcrysgrow.2006.09.001.

[18]. M. Fiederle et al., “Modified compensation model of CdTe,” J. Appl. Phys., vol. 84, no. 12, pp. 6689–6692, Dec. 1998, doi: 10.1063/1.368874.

[19]. J. Sites and J. Pan, “Strategies to increase CdTe solar-cell voltage,” Thin Solid Films, vol. 515, no. 15, pp. 6099–6102, May 2007, doi: 10.1016/j.tsf.2006.12.147.

[20]. N. Amin, K. Sopian, and M. Konagai, “Numerical modeling of CdS/CdTe and CdS/CdTe/ZnTe solar cells as a function of CdTe thickness,” Sol. Energy Mater. Sol. Cells, vol. 91, no. 13, pp. 1202–1208, Aug. 2007, doi: 10.1016/j.solmat.2007.04.006.

[21]. M. Barbato et al., “CdTe solar cells: technology, operation and reliability,” J. Phys. Appl. Phys., vol. 54, no. 33, p. 333002, Aug. 2021, doi: 10.1088/1361-6463/ac04e3.

[22]. G. Khrypunov, A. Romeo, F. Kurdesau, D. Batzner, H. Zogg, and A. Tiwari, “Recent developments in evaporated CdTe solar cells,” Sol. Energy Mater. Sol. Cells, vol. 90, no. 6, pp. 664–677, Apr. 2006, doi: 10.1016/j.solmat.2005.04.003.

[23]. R. M. Geisthardt, M. Topic, and J. R. Sites, “Status and Potential of CdTe Solar-Cell Efficiency,” IEEE J. Photovolt., vol. 5, no. 4, pp. 1217–1221, Jul. 2015, doi: 10.1109/JPHOTOV.2015.2434594.

[24]. R. W. Birkmire, B. E. McCANDLESS, and S. S. Hegedus, “EFFECTS OF PROCESSING ON CdTe/CdS MATERIALS AND DEVICES,” Int. J. Sol. Energy, vol. 12, no. 1–4, pp. 145–154, Jan. 1992, doi: 10.1080/01425919208909758.

[25]. K. D. Dobson, I. Visoly-Fisher, G. Hodes, and D. Cahen, “Stability of CdTe/CdS thin-film solar cells,” Sol. Energy Mater. Sol. Cells, vol. 62, no. 3, pp. 295–325, May 2000, doi: 10.1016/S0927-0248(00)00014-3.

[26]. Y. Zhang, W. Chen, J. Zhang, J. Liu, G. Chen, and C. Pope, “In Vitro and In Vivo Toxicity of CdTe Nanoparticles,” J. Nanosci. Nanotechnol., vol. 7, no. 2, pp. 497–503, Feb. 2007, doi: 10.1166/jnn.2007.125.

[27]. M. A. Berding, “Native defects in CdTe,” Phys. Rev. B, vol. 60, no. 12, pp. 8943–8950, Sep. 1999, doi: 10.1103/PhysRevB.60.8943.