



CdSe AND CdSeTe THIN FILMS FOR SOLAR CELL APPLICATION

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Abstract

The most dependable technique for meeting the need for energy in the future is photovoltaic (PV) technology. This technology can also provide an effective solution to the mass destruction of nature. Semiconducting thin film solar cells have attracted much attention due to their potentials in efficiency as well as cost. CdSe and CdSeTe thin films are intriguing materials for the realization of electronic and photoelectronic devices for energy conversion. Many researchers have reported about these materials prepared by different techniques and their properties as well as their use in photoelectrochemical cells fabrication. The aim of this paper is to review the development achieved in previous years in the field of monocrystalline, polycrystalline and thin-film PVs.

Keywords: Bulk-Hetero Junction (BHJ), Solar Cells, SCLC, Power conversion efficiencies (PCE).

INTRODUCTION

The demand of energy has been increasing day by day and it has been predicted that the demand of energy in 2035 will be 7.247×10^{18} J and 30TW is estimated for 2050. The nonstop conversion of solar energy into electrical energy is essential so as to accomplish the energy need of the present world¹. The conversion of sunlight into electricity can be done with solar cells, also called photovoltaics (PV). Therefore the requirement of an efficient solar cell will be crucial for such energy conversion in order to meet the world energy consumption. Traditionally, PV materials are the inorganic semiconductors which can form suitable junctions with other materials. Several semiconducting materials have been shown a PV effect, but only a few of them have sufficient commercial interest due to satisfying essential constraints to minimising the thickness and their enough availability. Ideally, absorber material must have an efficient high absorption coefficient ($10^5/\text{cm}$) of terrestrial light and direct energy bandgap semiconductor with a bandgap of 1.5 eV, high quantum efficiency of excited carriers, long diffusion length and low recombination velocity. Material should have ability to form a good electronic junction (homo/hetero/Schottky) with suitably compatible materials. The high optical absorption defines the optimum thickness of an absorber in a solar cell because order of a film thickness inverse of the optical absorption coefficient. To minimize the processing and manufacturing difficulty the elemental materials should be chosen as simplest as possible. Edmond Becquerel discovered the PV effect in 1838, when he observed a small voltage and current when two silver halide coated platinum plates immersed in an acidic solution were exposed to light². In 1877, Charles Fritts constructed the first true solar cells (at least, the first resembling modern cell made from only solid materials) by using junctions obtained by coating the semiconductor selenium with an ultrathin, nearly transparent layer of gold. Fritts's device was very inefficient, transforming less than 1% of the absorbed light into electrical energy³. Later (in 1946), Russell Ohl patented the modern junction semiconductor solar cell⁴.

The modern era of PV started in 1954 when Chapin, Fuller and Pearson obtained a solar efficiency of 6% for a Si junction cell⁵. The attempts for the fabrication of solar cell are categorized in Four generations. The first generation is Si wafer (Single-crystalline and multi-crystalline) based PV device wafers. For efficient absorbance, a thick layer of silicon is required because Si have indirect band gap so a thick material is needed for high absorption⁶. Second generation solar cells are based on the thin-film deposits of semiconductors, such as amorphous Si, CdTe, CuInGaSe₂ or CuInS₂⁷. The third solar cells are organic and dye sensitized solar cells. The theoretical efficiency limit is greater than 41% for single E_g solar cells⁸, does not rely on a traditional p-n junction to separate photogenerated charge carriers^{9,10} and having low cost technology as found in tandem solar cell¹¹, dye-sensitized solar cells¹², and polymer solar cell (combination of small organic molecules and conjugated polymer)^{13,14}. The fourth generation of solar cells known as bulk-hetero junction (BHJ) solar cells provides the combined advantages of both organic and inorganic semiconductors. Hybrid PV devices contain conjugated polymers that absorb light as the donor and transport holes¹⁵. Over the last few years, Pb and Cd chalcogenide (PbX and CdX, X= S, Se or Te) nanocrystals (NCs) attracted more attention in BHJ solar cells due to their tenability of E_g via size control¹⁶ and possible multiple exciton generation (MEG)¹⁷⁻¹⁹. Furthermore, the performance of Pb and Cd chalcogenide NCs based BHJ solar cells strongly depends on their size and interface structure in the polymer matrix. Due to simplicity in junction fabrication and inbuilt storage capacity, semiconductor/Si junction cells have attracted a great deal of interest over p-n junction solar cell²⁰. The thin film of a material creates ab initio by the random nucleation and growth processes of individually condensed/ reacting atomic/ ionic/ molecular species on a substrate. The structural, chemical, metallurgical and physical properties of such materials strongly depend on a large number of deposition parameters and thickness. Advantage of thin-film it may encompass a considerable thickness range with varying from a few nanometers to tens of micrometers: might be best defined in terms of the birth processes. Thin films of the material can be produced by a number of existing methods

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with the geometrical control. Ideally an efficient solar cell material thin film should have properties such as high absorption coefficient as it require less thickness and consume less material, microstructure of the film from one extreme of amorphous/nanocrystalline to highly oriented and/or epitaxial growth should be controlled by the deposition parameters and substrate or used technique, surfaces modified to achieve desired optical reflectance/transmission characteristics and optical trapping effects, Surface and interface of the materials should modify to get an interlayer diffusion barrier and surface electric field etc.

Semiconducting thin films play a very important role in the research to the development of solar cells and many optoelectronic devices. Compound semiconducting materials formed by combining elements of groups in the periodic table such as III-V, II-VI, I-VII, II-V, V-VI, and IV-V compounds have a wide range of physical properties, which include band gap, crystal lattice structures, electron and hole mobility that can be used for many applications. II-VI semiconductors are compound semiconductors formed by group IIB metallic elements (Cd, Zn, and Hg) with group VI nonmetallic elements (O, S, Se, and Te). These materials have drawn significant interest because of their capability to behave as a wide-bandgap (1.5–3.5 eV) material as well as a narrow-bandgap (0–1.5 eV) material. The synthesis of binary metal chalcogenides of group II-VI (CdS, CdSe, ZnS, ZnSe, CdTe) in nanocrystalline form is a rapidly growing area of research due to their important nonlinear optical properties, luminescent properties, quantum size effect and other important physical and chemical properties. During the last decade, extensive research work has been carried out on CdSe, CdTe, and ZnSe thin films due to their potential applications in optoelectronic devices; their band gap lies near the peak of the solar energy spectrum. CdSe is an important member of this group of compounds because of its extensive use in different fields such as biomedical technology, solar cell technology²¹⁻²³, chemical sensing, thin film transistors, photoconductors, acousto-optical devices, gas sensors, photo electrochemical devices²⁴, and photoreceptors. CdSe is an n-type direct bandgap semiconducting material. The bulk bandgap energy of 1.74 eV at 300K is very close to the NIR, which can be increased through a variety of processes. The reported molecular weight is 191.37 g/mole in which Cd is 58.74% and Se is 41.26% and has a dark red color in appearance²⁵. Different fabrication techniques have been reported to grow thin films of CdSe which includes the chemical bath deposition technique^{26,27}, molecule beam epitaxy²⁸, electrodeposition²⁹, spray pyrolysis, successive ionic layer adsorption and reaction³⁰, thermal evaporation^{31,32}, and MOVCD³³. In recent years cadmium chalcogenide compounds have been extensively investigated because of their potential applications in solar energy conversion. CdSe_xTe_{1-x} pseudo binary compounds of CdSe and CdTe find applications in photovoltaic or photo electrochemical devices. CdSe_xTe_{1-x} thin films are interesting materials because their band gap lies in the optimal range (1.3–1.7 eV) required for a photovoltaic cell. The ideal band gap for a solar cell is 1.4 eV. Such band gap values can be easily achieved with CdSeTe mixed compounds.

Material properties of CdSe films

CdSe has found to form in both sphalerite (cubic, zinc blende) and also wurtzite (hexagonal) structure. Although most of the researchers have reported hexagonal structure with the c axis

oriented normal to the substrate surface, there are studies indicating the cubic structure for the CdSe polycrystalline thin films. CdSe thin films with absorption edge at about 700 nm have a direct band gap of 1.74 eV. The grain boundary defect governs the conduction process in compound thin films. Due to dangling bonds, the grain boundary of pure compound films like CdSe has a considerable number of defects³⁴. Excess cadmium and selenium vacancies are native defects of CdSe. As a result of these defects, CdSe frequently exhibits n-type conductivity in both bulk and thin films. Selenium-rich films, on the other hand, are likely to exhibit p-type conduction. Those defects effectively act as trapping or recombination centres, and they play a key part in the conduction processes. The concentration of native defects in these thin films is determined by the film growth environment³⁴. Oduor et al performed high field measurements on thermally evaporated CdSe films using sandwich geometry and their results were interpreted as ohmic conduction at low voltages and SCLC dominated by an exponential trap distribution at higher voltage levels³⁵. Polycrystalline CdSe films prepared by the vacuum evaporation technique with different thickness and at different substrate temperatures have been analysed by D. Pathinettam Padian et al³⁶. The films showed hexagonal structure and the crystallinity increased with an increase in the substrate temperature. The band-gap values decreased with increase in thickness and substrate temperature. The electrical conductivity measurements showed three different activation energies in the temperature range from 298 to 118 K. The steady-state photoconductivity measurements revealed that the photocurrent varied with the applied voltage and the photocurrent obeyed a power law of the form, I_{ph} proportional to γ where gamma is a constant.

Shreekanthan et al³² reported preparation of cadmium selenide thin films by thermal evaporation technique. They got homogeneous, stoichiometric thin films of cadmium selenide. The films deposited at room temperature were cadmium rich with segregated selenium globules. The obtained films are found to be n-type with low resistance. The structural and optical properties of thermally evaporated CdSe thin films were studied by Cristian Baban et al³¹. The as-deposited films were polycrystalline in nature with hexagonal structure and have preferred orientation in the (002). The grain size was in the range of 20nm-100nm and increased with the substrate temperature. The optical band-gap was in the range of 1.65eV to 1.75eV.

Kalita et al³⁷ studied the space charge limited conduction in thermally evaporated CdSe films of 85 -300 nm. The detailed study of the I-V curves of the films deposited between 303K and 573K in dark and also under illumination, revealed that the conduction mechanism was ohmic at low voltage and trap limited Space Charge Limited Conduction (SCLC) at a higher voltage. The transition voltage (V_t) from ohmic to SCLC is found to be independent of ambient temperature as well as intensity of illumination. Trap depth was estimated to be within 0.60-0.37eV and the trap depth decreases with an increase substrate temperature and thickness. Also the ratio of injected charge to free charge (θ) and the free carrier electron density (n_0) increases with an increase of ambient temperature and the intensity of illumination, however with a decrease in the total trap density (N_t). The electrical properties of non-irradiated and electron irradiated polycrystalline CdS and CdSe prepared by thermal evaporation technique at 220°C films, sandwiched between two gold electrodes, were investigated

by S. Antohe et al³⁸. The current voltage characteristics, recorded in the temperature range of 150-400 K, showed ohm's law is followed at low-applied voltages, in both non-irradiated and irradiated CdS and CdSe layers. In the high-applied voltages, the dominant conduction mechanism is the space charge limited current (SCLC) as explained in the frame of SCLC theory.

S. Velumani et al³⁹ studied the dielectric and conduction studies behaviour of hot-wall deposited CdSe films. The films have (002) preferred orientations with wurtzite structure. The EDAX analysis revealed an increase in Cd content with an increase in the thickness. Dielectric constant was found to be high under illumination compared to dark. The capacitance and dielectric constant reached a saturation point at higher frequencies. The activation energy was found to be frequency dependent and found to be high under dark than under illumination. The Mott-Scotty plot showed the conductivity as n- type. The higher values of flat band potential and the open circuit voltage predicted that the hot-wall deposited CdSe films were suitable for photovoltaic applications.

The effect of femtosecond laser pulse illumination on photoluminescence (PL) properties of CdSe nanocrystalline films prepared by chemical bath deposition technique on silicon substrate was analyzed by M. Simurda et al⁴⁰. A substantial PL efficiency enhancement (up to 20X) and modification of PL spectrum were dependent on ambient atmosphere and illumination intensity. Baban et al⁴¹ investigated the effect of preparation conditions on the structure and optical properties of CdSe thin films deposited under vacuum by thermal evaporation. The average size of the crystallites increases with increasing substrate temperature and the temperature of the evaporation source. The deposition parameters found to have a significant influence on transmission spectra.

Results on CdSe based photo electrochemical solar cells prepared by the brush plated technique at a higher substrate temperature were presented by K.R.Murali et al⁴². The films were prepared on the substrate which is maintained at different temperatures in the range of 30-90°C. The optical band gap energy was found to be 1.65eV and the capacitance –voltage measurement indicates n- type behavior. The cells exhibit higher efficiency and the spectral response measurements indicate a peak quantum efficiency of 75% at 1.65 eV.

A.V. Kokate et al⁴³ electrochemically deposited stoichiometric thin films of CdSe onto the stainless steel and fluorine doped tin oxide (FTO) coated glass substrates at 80 °C; thin films are polycrystalline with cubic structure and showed direct transition with a band gap of 1.72 eV. The XRD pattern contained sharp peaks at (111), (220), (400), (331) and (440). Structural and optical properties of electron beam evaporated CdSe films was analysed by N.J.Suthan et al⁴⁴ and showed hexagonal phase with (002) orientation. The crystalline size increased from 24 nm to 64 nm for a thickness variation from 120 nm to 710 nm, whose band gap values are about 1.92 eV. Y.G Gudage et al⁴⁵ studied the photovoltaic properties of electrodeposited CdSe films on Stainless Steel (SS), Titanium (Ti) and FTO (Fluorine doped Tin Oxide) substrates. The film thickness increased with the deposition time and the deposition potential decreased with increased bath temperature. The grain size of the FTO coated substrates showed higher crystalline size than the other films and they showed better solar cell

performance. CdSe films have been prepared by M.A. Perez et al⁴⁶ using CBD and Pulsed Laser Deposition (PLD) techniques. The effects of the bath temperatures (30–90°C) and the Cd/Se ratio on film properties were investigated. PLD films show better crystalline quality and higher crystalline size. Annealing transformed the metastable cubic phase into the hexagonal phase and showed a “red shift” in the band gap of the CBD and PLD films. CdSe films deposited by vacuum evaporation technique have been analyzed by D. Patidar et al⁴⁷. As deposited films are polycrystalline with preferred orientation along (002) plane and the band gap was about 1.67 eV. I-V measurement revealed a conductivity increases with the increase of temperature. Polycrystalline CdSe films were deposited using sintering process by Sharma et al⁴⁸. Band gap values increased with increase in temperature and time, showing polycrystalline nature with zinc blende structure.

Mahfoz Kotb et al⁴⁹ reported temperature dependence of D.C. conductivity of as-prepared and annealed CdSe thin films. The experimental results indicate that the electrical conduction taking place through the thermally activated process. They reported at higher temperatures, electrical conduction for the as-prepared film is taking place in the extended states while localized states conduction in the band tails is most likely to take place for annealed films. In the lower temperature range, conduction by hopping in the localized states near the Fermi level is found to be dominant.

Singh et al⁵⁰ prepared CdSe semiconductor films on glass substrates by Chemical bath deposition. SEM studies shows ball type structures with approximate grain size ranging between 4 nm and 8 nm with voids on uniform background. XRD measurement shows that the film is crystallized in the hexagonal wurtzite phase and presents a preferential orientation along the c-axis. PL emission spectra (under 389 nm excitation) exhibits blue shift (nano-crystalline effect), consisting of two peaks at 485 nm and 531 nm wavelengths which are attributed to the presence of one deep trapping site and electron hole recombination via trap state or imperfection site. The deposited crystalline CdSe thin film was suitable for many optical devices, such as solar cells, because of well-crystallized, high transmittance in visible region (> 80%) and suitably wide band gap value. CdSe quantum dots have been prepared with different sizes and exploited as inorganic dye to sensitize wide bandgap TiO₂ thin films for QDs solar cells by Kashyout et al⁵¹. The synthesis is based on the pyrolysis of organometallic reagents by injection into a hot coordinating solvent. XRD, HRTEM, UV-visible, and PL were used to characterize the synthesized quantum dots. CdSe quantum dots with sizes ranging from 3 nm to 6 nm were obtained which enabled the control of the optical properties and consequently the solar cell performance. Solar cell of 0.08% performance under solar irradiation with a light intensity of 100 mW/cm² has been reported.

Yukselici et al⁵² reported growth of CdSe thin films on glass substrates by physical vapor deposition. They studied the optical and structural properties of grown CdSe thin films. The redshift in the asymptotic absorption edge with film thickness was related to an increase in the average size of grains grown during PVD process. The crystal-structure-dependent luminescence properties of CdSe quantum dots (QDs) in their cubic zincblende (*Zb*-CdSe) and hexagonal wurtzite (*Wz*-CdSe) phases have been investigated by Subila et al⁵³, maintaining their optical band gaps as well as the relative

ratios of capping ligands the same. The *Zb*-CdSe QDs exhibited excellent photostability and high photoluminescence quantum yield ($\phi_L = 0.375$) compared with *Wz*-CdSe QDs ($\phi_L = 0.046$). Detailed X-ray photoelectron spectroscopic (XPS) investigation revealed that the surface of *Zb*-CdSe is rich with Cd^{2+} ions, which leads to the formation of CdO layer. The thickness dependent physical properties of CdSe thin films are reported Purohit et al⁵⁴. Films of thickness 445, 631 and 810 nm were deposited employing thermal evaporation technique followed by thermal annealing at 200 °C. The structural analysis showed that the films were nanocrystalline in nature with cubic phase having preferred orientation (111). The intensity of prominent peak was found to be increased with thickness owing to increase in the crystallinity. Despite the fact, the crystallinity of films of thickness 631 nm was found to decrease due to stacking of new smaller grains on the surface of larger grains. Consequently, the behavior of structural and optical parameters was changed and opposite behavior was observed for this thickness. The optical band gap was found in the range 1.75–1.92 eV and observed to increase with thickness. The SEM analysis showed that the annealed films were uniform, fully covered and well defined while some crystal defects such as cracks and pin holes were observed. The electrical analysis showed that the variation in current with voltage was found to be linear and resistivity was observed to vary with film thickness.

Jamble et al⁵⁵ synthesized cadmium selenide (CdSe) nanoparticles by using cadmium chloride (CdCl_2) as cadmium ion and sodium selenosulfate (Na_2SeSO_3) as selenium ion sources through a hydrothermal route at 180 °C temperature for 24 h. Aqueous ammonia was employed as a complex reagent to adjust the pH of the solution. Structural analysis revealed that CdSe has a cubic structure with average crystallite size 13.15 nm. SEM and TEM studies confirmed cauliflower-like CdSe nanostructures. The electron diffraction pattern reveals the polycrystalline nature of CdSe. From UV–visible absorption spectral analysis, the optical energy bandgap of CdSe nanoparticles was found to be 1.90 eV. The CdSe nanoparticles exhibit photoluminescence with two distinct emission bands at 632 nm and 720 nm. CdSe thin films of various thicknesses deposited on ITO glass substrates by electrodeposition technique is reported by Choudhary et al⁵⁶. Deposited Polycrystalline thin films have cubic structure; the crystalline nature and optical quality get enhanced with film thickness. Optical analysis shows that the CdSe thin films possess direct band gap which decreases from 2.67 to 2.47 eV with the increase in thickness. Electrical analysis (I–V characteristics) showed that the resistivity of CdSe thin film decreased with increase in thickness.

CdSe films with few nanometer thicknesses were deposited by chemical bath deposition technique on the glass substrates at low temperature (<100°C) and analyzed by Hussain et al⁵⁷. Thin films deposited at different bath temperatures were initially amorphous in nature but after annealing at elevated temperatures, they transformed to polycrystalline thin films having cubic structure along (111) preferential direction. The grain size of the nanostructures increases from 2.23 to 4.13 nm as annealing temperatures increase from 100 to 400°C because small grains agglomerate together to form larger grains, which significantly influenced the optical properties of the films. The bandgap values decreased from 2.20 to 2.12 eV by increasing the deposition temperatures, and after annealing at the temperature of 400°C the bandgap energy further decreased to

1.73 eV. The values of the bandgap energy of the sample deposited at low temperature, below 100°C is located in the visible region of the solar spectrum. Hence, the films can be used in solar energy architecture as energy harvester.

Material properties of CdSeTe films

Ternary alloys of CdSe and CdTe compound semiconductors are potential and interesting candidates in the field of optoelectronic devices. The major advantages of these materials are their stability as nano-crystallites, excellent photoelectric properties with high optical absorption, and most favorable band gap for solar energy conversion⁵⁸. Recent investigations have suggested that CdSe may be a suitable choice to alloy with CdTe in hopes of increasing power conversion efficiencies (PCE)⁵⁹. While CdSe exists in the wurtzite ground state, $\text{CdSe}_x\text{Te}_{1-x}$ alloys have been shown to remain stable in either the zincblende⁶⁰ or wurtzite⁶¹ structure depending on the concentration and temperature of synthesis. As the lattice mismatch of CdTe and CdSe is relatively small (~6% difference in lattice constant⁶², the solubility of Se into Te is higher and the defect density is low, allowing for minimal effects on the recombination rate⁶³. Although the band gap of CdSe (1.70 eV)⁶⁴ is higher than that of CdTe (1.50 eV)⁶⁵, bowing effects cause the band gap to decrease at low to intermediate Se concentrations, resulting in enhanced PCE as the gap approaches the ideal Shockley-Queisser value⁶⁶. Additionally, as $\text{CdSe}_x\text{Te}_{1-x}$ spans a wide range of band gaps (1.3–1.7 eV), a graded absorber layer may be utilized to gain a greater degree of absorption throughout wavelengths in the visible spectrum⁶⁷.

Se and Te are elements of the same group of the periodic table. When Te is added to pure Se, some of the Te atoms may not be incorporated in chains. In this case, some of the Te act as ionized impurities, since the electron affinity of Te is lower than that of Se. Te atoms were therefore expected to form positively charged localized states. Similarly, the addition of Cd could induce more positively charged localized states, since its electron affinity is much lower than those of Se and Te.

S.K. Tripathi et al⁶⁸ have reported their photoconductivity measurement in the binary Se-Te and the ternary Se-Te-M (M=Cd, In and Sb) glassy. They found that in the amorphous state the photosensitivity decreases after the incorporation of Cd, In and Sb in the binary $\text{Se}_{80}\text{Te}_{20}$ alloy. However, after crystallization, photosensitivity decreases quite significantly in case of $\text{Se}_{80}\text{Te}_{10}\text{In}_{10}$ and $\text{Se}_{80}\text{Te}_{10}\text{Sb}_{10}$ whereas; an increase in the photosensitivity is observed in the case of $\text{Se}_{80}\text{Te}_{10}\text{Cd}_{10}$. Dielectric properties in the same glassy system have been reported by R. Arora et al⁶⁹ and interpreted their results in terms of a theoretical model which considers hopping of charge carriers over a potential barrier between charge defect states (D^+ and D^-). Fayek et al⁷⁰ prepared amorphous CdSeTe films of composition in the range 0–10 at.% Cd and with a thickness of about 200 nm by thermal evaporation technique. The optical band gap was found to be in the range 0.5–1.0 eV and arose from indirect transitions. The electrical properties of Cd thin films shows Ohmic conduction at low electric fields resulting from the thermal excitation of carriers from centers in the band gap. At low enough temperatures, the dominant conduction may take place via hopping, whereby carriers hop from occupied to unoccupied sites located within a band of localized states situated within the band gap.

Singh et al⁷¹ studied I-V characteristics of amorphous thin films of $\text{Se}_{80-x}\text{Te}_{20}\text{Cd}_x$ ($x=0,5,10,15$) glassy systems and Density of localized states (DOS) near Fermi level is calculated from the fitting of the data in the theory of SCLC. It was found that the addition of Cd could not change DOS significantly in pure binary Se-Te glassy network. Muthukumarasamy et al^{72,73} deposited $\text{CdSe}_x\text{Te}_{1-x}$ ($x = 0.15, 0.4, 0.6, 0.7$ and 0.85) thin films of different compositions on glass substrates by hot wall deposition method. The deposited films reported to be crystalline in nature and exhibit either cubic zinc blende or hexagonal phase or both depending on the composition of the material. Optical spectra show a sharp fall in transmittance at wavelength corresponding to the band gap of the material. The optical band gap found to be direct allowed and strongly depends on film composition allowing tailoring the band gap as required for solar cell applications. The variation of band gap with composition has been observed to be quadratic in nature exhibiting a bowing behaviour.

Murali and Jayasutha^{74,75} reported the hexagonal phase for the $\text{CdSe}_{1-x}\text{Te}_x$ films deposited on titanium and conducting glass substrates by brush plating at different temperatures in the range of 30–80 °C. The crystallite size increased from 30 to 100 nm as the substrate temperature increased. The resistivity of the films decreased with increase of substrate temperature. The carrier density and mobility increased with substrate temperature. Optical band gap of the films shows the linear variation and varied in the range of 1.45–1.72 eV. Shinde et al⁷⁶ deposited $\text{CdSe}_{0.6}\text{Te}_{0.4}$ thin films onto glass and FTO coated glass substrates by facile chemical bath deposition (CBD) method. The films are polycrystalline in nature exhibiting hexagonal crystal structure. FESEM analysis showed the formation of 3D flowerlike $\text{CdSe}_{0.6}\text{Te}_{0.4}$ nanostructures composed of number of flake-like thin nanopetals. Optical absorption study revealed the band gap energy of 1.61 eV and water contact angle of $\text{CdSe}_{0.6}\text{Te}_{0.4}$ thin film lies in the hydrophilic regime which enhances the intimate contact at electrode/electrolyte interface. The photo-conversion efficiency and fill factor of prepared photo-electrochemical cell are found to be 0.43% and 0.58, respectively.

To achieve high efficiency single and multijunction solar cells, controlling of the band gap of the absorber layer is required. Swanson et al⁷⁷ reported that the addition of CdSeTe layers results in the improved current collection at long wavelengths. $\text{CdSe}_{1-x}\text{Te}_x$ thin films was grown by varying x (0 to 1) using thermal evaporation method by Santhosh et al⁷⁸ and optical band gap of CdSeTe alloyed thin films was measured to evaluate material behavior as the Te incorporation increased in the films. It was found that optical band gap can be tuned from 1.67eV to 1.51eV as value of x varied from 0 to 1. Lingg et al⁷⁹ prepared 5–10 μm thick layers of $\text{CdTe}_{1-x}\text{Se}_x$ alloy, with $x = 0-0.5$ by co-evaporation of CdTe and CdSe. The structural, optical, and electronic properties of $\text{CdTe}_{1-x}\text{Se}_x$ films are examined for different Se concentrations and a bowing of the optical band gap was observed with a minimum of 1.40 eV around $x = 0.3$. The findings reveal that $\text{CdTe}_{1-x}\text{Se}_x$ can be used to fabricate solar cells with increased photocurrent coupled with the possibility of introducing doping gradients into $\text{CdTe}_{1-x}\text{Se}_x$ solar cells. DC electrical conductivity was calculated using I-V characteristics, recorded at different temperatures in $\text{Se}_{70}\text{Te}_{30-x}\text{Cd}_x$ ($x=1,2,3,4$ & 5) glassy systems by V. K. Saraswat⁸⁰. It was reported that the

conductivity increases with the increase of Cd content which may be due to the reason that concentration of higher energy bonds of Cd-Se is increased. The linearity of $\ln(I)$ versus $V^{1/2}$ curves suggests that these glasses obey the Poole-Frenkel conduction mechanism.

Dumre et al⁸¹ employed first principles methods based on density functional theory and beyond to study $\text{CdSe}_x\text{Te}_{1-x}$ alloys in the zincblende and wurtzite structures. Strong bowing effects in the band gap and effective electron/hole masses were noticed due to local structural distortions. Downward bowing in the band gap and effective hole mass of the zincblende structure have potential benefits in photovoltaics through increased net photocurrent. The presence of short-range order characterized by clustering among like atoms results in minimization of strain. Their findings suggest that alloying zincblende $\text{CdSe}_x\text{Te}_{1-x}$ throughout $x = 0.2-0.5$ is likely to provide the most beneficial effects for photovoltaics given the band gap within this range is near the ideal value of 1.4 eV, which may also allow enhanced net photocurrent.

Thin films of cadmium chalcogenide ($\text{CdSe}_{0.2}\text{Te}_{0.8}$) have been prepared by the radio frequency magnetron sputtering with different thickness on to the glass substrates by Guangqiang et al⁸². The films obtained have cubic zinc-blende structure with no secondary phases. Reported values of band gap of $\text{CdSe}_{0.2}\text{Te}_{0.8}$ varied slightly in the range 1.41–1.43 eV with the film thickness. The thickness $d = 880$ nm of $\text{CdSe}_{0.2}\text{Te}_{0.8}$ film is sufficient to absorb most of visible light and as such as-prepared $\text{CdSe}_{0.2}\text{Te}_{0.8}$ could serve as a photovoltaic absorption layer in ultra-thin solar cells.

Wang et al⁸³ reported that the electron lifetime in the CdSeTe alloyed system is higher (improved) than that in the CdTe-based system, by using first-principles calculations and the low energy $\Sigma 3$ (112) grain boundary (GB) in polycrystalline CdTe. In the alloyed system, Se has the tendency to move toward the $\Sigma 3$ (112) GB. Consequently, Se at the GBs in CdTe can effectively passivate the deep GB defect levels, thus reducing carrier recombination and improve solar cell performance. The $\Sigma 3$ (112) GB with Te-core has the lowest formation energy among the electronically detrimental GB configurations in polycrystalline CdTe and introduces a deep defect state in the bandgap of CdTe, which can act as nonradiative recombination center and reduces the carrier lifetime of CdTe. When Se segregates to GB and substitutes the Te atom at the Te dimer site, due to the lower energy of Se 4p orbital and the weak coupling between the dimer elements in the GB core, the deep GB states will shift to shallower states toward the valance band maximum of CdTe thereby increasing the carrier lifetime of the CdSeTe layer resulting in the improved lifetime and performance of Se-alloyed CdTe solar cells.

Conclusion

Cadmium chalcogenides CdTe, CdSe and their mixed ternary alloy $\text{CdSe}_x\text{Te}_{1-x}$ have semi-conducting properties, which are especially suitable for the conversion of solar energy to electrical energy in photovoltaic or photo electro-chemical devices. Alloying CdSe with CdTe to form $\text{CdSe}_x\text{Te}_{1-x}$ alloys could be an effective approach to increase the PCE of the CdSe based thin film solar cells. These materials can be used to engineer the lattice parameters and bandgap for heterostructure. The study of properties of such ternary alloys opens the door for many innovations. Employing low cost

preparation methods to grow such ternary alloys with different composition for various large area devices may be an area worth pursuing.

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