Effect of annealing on structural, morphological and optical properties of CdTe/(Cd-Zn)S thin films

Devjyoti Lilhare* and Ayush Khare

Thin Film Laboratory, Department of Physics, National Institute of Technology
G E Road, Raipur – 492 010 India

*Corresponding author’s e-mail address dev17jyoti@gmail.com

Abstract. Here, we present the results of an investigation on structural, morphological and optical properties of CdTe/(Cd-Zn)S films deposited on FTO substrate through electrodeposition technique for solar cell application. The deposited films were heat-treated in the presence of CdCl2 for the recrystallization. Various techniques, such as X-ray diffraction (XRD), field emission scanning electron microscopy (FESEM), high-resolution transmission electron microscopy (HRTEM), optical studies (absorption, transmission, band-gap and photoluminescence studies) were employed to examine the structural, morphological and optical properties. XRD spectra show the preferential orientation (111) in CdTe films. Uniform and bounded grains are observed upon annealing of the films. The changes in CdTe film were attributed to nucleation of the CdTe grains during the CdCl2 treatment. The band-gap (Eg) value for CdTe estimated from absorption spectra and corresponding Tauc’s plots comes to be ~1.50 eV. Summary of results suggests that the annealing of different component films is helpful in improving solar cell performance.

Keywords: (CdTe)/(Cd-Zn)S/FTO; CBD; electrodeposition; annealing; solar cell

1. Introduction
In the future, solar power generation will serve as a source of energy. Due to the less material usage and lower cost manufacturing processes, thin film solar cells have emerged to become the future of solar energy technology. In photovoltaic (PV) technology, Cadmium telluride (CdTe) has the potential to become a leading energy producer in industry of solar energy in the coming decades. CdTe is positioned to possess a high absorbance coefficient. It can be easily deposited by high growth-rate processes, and has an optimum band-gap (~1.50 eV). Thus, it has a high potential as a thin-film solar cell absorber layer on an industrial level [1]. During last many years, CdTe/(Cd-Zn)S thin film heterostructure has attracted researchers for intense research in PV community [2-19].

In CdTe/(Cd-Zn)S solar cells, (Cd-Zn)S film (100 nm) absorbs 36% of the incident photon with energy higher than the band-gap energy [20]. CdTe has the direct optimum band-gap with over 5 × 107/cm absorption coefficient defining that a large amount of the energetic photons with higher energy than the energy of band-gap can be absorbed within a few μm of absorber layer of CdTe [21] and only
a thin layer of the material is needed for total absorption of the solar spectrum (<2 µm). These characteristics make it an ideal material for PV conversion.

Various established techniques, such as spray pyrolysis, electrodeposition (ED), sputtering, close spaced sublimation (CSS) and chemical bath deposition (CBD) have been used to grow (Cd-Zn)S layers [22-26]. There are two different categories to divide these techniques; (i) low-temperature and (ii) high-temperature. In CBD and ED techniques, produces (Cd-Zn)S layers below the 100 °C temperatures and for device fabrication as-deposited layers are not suitable. So, in order to get better the structural, optical and electrical properties of these layers, they must go through the heat treatment at approximately 400 °C for 20 min in air before the CdTe deposition over the glass/FTO/(Cd-Zn)S substrates. Heat treatment in air generally advances the crystallinity, and enhances the properties of the materials. (Cd-Zn)S used as a window layer material with the wide band-gap (E_g= 2.46 eV) has been deposited by CBD technique and the CdTe used as absorber layer material with narrow band-gap (E_g~1.50 eV) was grown by the electrodeposition technique. CBD is a popular method for depositing (Cd-Zn)S films [27]. Xu et al. reported the efficiency of the CdTe/(Cd-Zn)S solar cell increased from 15.42% to 17.71% [28]. The chemically deposited (Cd-Zn)S films have a tendency to form the mixed phases (cubic and hexagonal), and therefore they come with poor crystalline quality. So, for the enhancement of optical and electronic properties annealing treatment becomes necessary to the chemically deposited (Cd-Zn)S films. Annealing is the effective method to enhance the properties of the films [29]. CdCl_2 treatment is also very effective to activate the cells. Following treatment with CdCl_2, film recrystallizes into the hexagonal phase, resulting in improved crystallinity and a lesser defects density [30]. CdCl_2 treatment can also improve the doping (n-type) of (Cd-Zn)S films, resulting in a higher built-in capacity in the CdTe film, leading to increased photovoltage [31]. CdTe–(Cd-Zn)S inter-diffusion is also affected by the CdCl_2 treatment [32]. Because of the large lattice mismatch at the interface of CdTe/(Cd-Zn)S, good solar cells are achieved by regulating S and Te interdiffusion [33, 34].

In this work, CdTe/(Cd-Zn)S films were deposited onto a FTO substrate by electrodeposition technique. Structural, optical and morphological properties were investigated using different techniques. Annealing effect has been at the focus of the work. The objective of our work is to differentiate the effect of annealing before and after CdCl_2 treatment films and to analyze the CdTe/(Cd-Zn)S/FTO film to enhance the knowledge about fabrication of thin film solar cell.

2. Materials and method
2.1. Materials
(Cd-Zn)S films are synthesized using cadmium acetate [Cd(CH_3COO)_2, 99.9% pure], zinc acetate [Zn(CH_3COO)_2, 99.9% pure] triethanolamine (TEA, 99.0% pure), thiourea (99% pure) and ammonia solution (NH_3OH, 25.0%) provided by Merck India. For CdTe electrolytic solution, cadmium sulphate (CdSO_4, 98% extra pure) from Loba Chemie, Tellurium Oxide (TeO_2, 99%) from Sigma-Aldrich, and Cadmium Chloride (CdCl_2, monohydrated pure) from Merck India, are used. All the chemicals are of analytical status and are used as received. Distilled water is used as a solvent for the preparation of different solutions.

2.2. Film deposition
We have worked on two types of films: annealed before CdCl_2 and annealed after CdCl_2 treatment. The CdTe/(Cd-Zn)S solar cell fabrication was as followed: a (Cd-Zn)S window layer was deposited on an FTO substrate using CBD technique. In the first film, (Cd-Zn)S is heat treated (annealed without CdCl_2) in air for 20 min at 400°C and dipped in to the electrolytic solution prepared by adding 1M solution of CdSO_4, a smaller amount (low concentration) of TeO_2, and 1000ppm level of CdCl_2. The pH was adjusted to 2.00 ± 0.02 through using NH_4OH or H_2SO_4 of high purity. In the second film, (Cd-Zn)S was directly placed into the electrolytic solution without any annealing. After the dip coating of CdCl_2 it was annealed for 20 min at 400°C. In both the cases, (Cd-Zn)S and CdTe [deposited on (Cd-Zn)S]) were used as window and absorber layer, respectively. In this deposition, 2-
electrode system was employed in the process of electroplating: (i) cathode: Glass/FTO and (ii) anode: high purity carbon electrode. Both the electrodes were immersed into an electrolytic solution. Full device structure was completed after forming back metal contact [glass/FTO/(Cd-Zn)S /CdTe/back metal contact] shown in figure 1.

Figure 1. Superstrate structure of a standard CdTe/(Cd-Zn)S Solar cell

2.3. Measuring instruments
In the way of identification of the structural classification and crystallographic orientation of the CdTe/(Cd-Zn)S films, PANalytical X’pert Multifunctional Powder X-ray Diffractometer (2θ= 20° to 80° and λ= 1.54 Å) at NIT Raipur is used. The applied operating voltage is 40 kV and current at 30 mA. The topographical study is done by using SIGMA Field Emission Scanning Microscope (CARL ZEISS EVO) at NIT Raipur, India. HRTEM studies are done using JEOL JEM-2100F/HR from IIT Kharagpur. The optical studies (absorption and transmission spectra) are done by using Shimadzu Make UV-1800 Spectrophotometer in the 600 nm to 1000 nm wavelength range at NIT Raipur. PL emission spectra are recorded using Shimadzu RF-5301 PC Spectrofluorophotometer at an excitation wavelength of 632 nm at NIT Raipur.

3. Results and discussion
3.1. Structural characterization
3.1.1. XRD studies
XRD is the first tool to identify the phases of prepared materials, their crystallinity and crystallite size within the layers. The typical XRD patterns of two different films (annealed before CdCl₂ and annealed after CdCl₂ treatment) are shown in figure 2. The XRD patterns reveal that the deposited films are polycrystalline in nature. The most intense peak in both the cases at (111) orientation is observed at 2θ= 24.11 which is identified as the zincblende structure. Another peaks of CdTe at (220) and (311) orientation (2θ= 39.40 and 2θ= 46.55, respectively) is observed only in before annealing case. These peaks are not observed in the film after annealing. The crystal structure of the film did not change upon annealing but another peak of cubic phase was missing in other film. The highly preferential growth along the particular crystallographic orientation of CdTe is (111) and other two peaks, (220) and (311) are extremely weak along the (111) plane. This entails that CdTe film became polycrystalline upon annealing. Similar trend is observed in the paper reported by Lee et al. [35]. They observed that annealing and CdCl₂ treatment made steadier zincblende structure of CdTe films and made CdTe films polycrystalline forms.
Figure 2. XRD Spectra of CdTe/(Cd-Zn)S film: (a) annealed before CdCl$_2$ treatment (b) annealed after CdCl$_2$ treatment

Table 1. XRD data of CdTe/(Cd-Zn)S films deposited on FTO substrate

| Sample                      | 20 (°) | d values (Å) | Intensity | FWHM (in radian) | hkl      | D (in nm) |
|-----------------------------|--------|--------------|-----------|------------------|----------|-----------|
| Annealed Before CdCl$_2$    | 23.862 | 3.72611      | 11779     | 0.027            | (111)c   | 54.79     |
|                             | 39.538 | 2.27747      | 5152      | 0.0224           | (220)c   | 68.31     |
|                             | 46.958 | 1.93342      | 3078      | 0.0169           | (311)c   | 93.38     |
| Annealed after CdCl$_2$     | 24.11  | 3.70611      | 13804     | 0.0177           | (111)c   | 83.79     |
|                             | 39.538 | --           | --        | --               | No peak  | --        |
|                             | 46.958 | --           | --        | --               | No peak  | --        |

In CdTe layers, the peak intensities, occurrence of peaks and angles can be accredited to the random grains orientation. In Table 1, the obtained XRD data and the structural parameters of CdTe/(Cd-Zn)S thin films are shown. The crystallite sizes (D) are determined using the Scherrer’s formula [36]:

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

where, $k = 0.94$, $\lambda = 1.54\AA$ (wavelength of the X-rays used), $\beta$ is FWHM of the diffraction peak (in radian) and $\theta$ is the Bragg’s angle.

Generally, it is considered that CdTe growth follows the structure zone model as reported by Luschitz et al. [37, 38] in which the structure of a grain was seen as a succession from needle like structure to a huge fine defined grain structure demonstrated at low to high temperature [38]. Similarly, the thickness of the film is also an affecting factor for the grain size [39]; hence, thicker films may have a bigger apparent size of grain. So, it is clear that the formation of the grain boundary in CdTe solar cells can influence the significant choice of deposition technique and conditions.
The recrystallization effect also affects the CdTe grain structure. But it occurs primarily for low temperature deposition, where the as-deposited (before CdCl₂ treatment) grain size is small and after CdCl₂ treatment, the size of the grain is considerably enhanced. [40-43]. In case of deposition at higher temperature, the grain size of as-deposited film is nearly similar to the treated grain size because of high temperature [44-46]. It may be possible due to the (Cd-Zn)S interface recrystallization [47]. Similar outcome can be seen in the article reported by Quadros et al. [48]. They reported that during the deposition at low temperature, in case of post-CdCl₂ treatment, CdTe recrystallizes to a much bigger grain size, but no change is observed in case of post-annealing at high temperature deposition.

This situation creates a difficulty while considering the structures of grains in CdTe solar cells. Sometimes, varied deposition methods become extremely difficult due to their conflicting results that it may be shift with respect to one another.

In the present case, it is concluded from Table 1 that the film annealed before CdCl₂ treatment has increasing grain size in spite of after CdCl₂ treated film. However, film after CdCl₂ treatment has higher intensity in (111) orientation so that grain size is also large as compared to the film before CdCl₂ heat treatment.

3.1.2 FESEM studies

FESEM is a useful tool to check the uniformity of large area material coverage. SEM is also widely used to determine the topographical image, shape and size of the grains and available defects/voids. For the improvement in thin film solar cells, deep knowledge of surface topography is very important. FESEM images of two different types of deposited films: annealed before CdCl₂ treatment and annealed after CdCl₂ treatment is shown in figure 3. In both the films, rose flower like structures are observed. This indicates the hydrophilic nature of CdTe/(Cd-Zn)S film. An overlapped layered growth structure and uniformity in nanoparticles are also observed that may be accredited to the chemically deposited (Cd-Zn)S films [49]. In figure 3(a), it is clearly evidenced that grains are agglomerated leading to large crystalline grains [50]. The effect of annealing on (Cd-Zn)S film (CdCl₂ heat treatment for 20 min at 400°C in air) showed a different result where crystallites are combined and bounded together to form large crystals and the clusters became large grains of CdTe. Grain sizes differ in few microns size, and these layers demonstrated similarity to the structure of CdTe grown by high temperature methods [51]. In duration of CdCl₂ treatment, a liquid surface is created at the grain boundary and Cl is easily moved along the grain boundary. Nevertheless, diffusion of Cl is sluggish in the crystalline material grains. For each CdTe grain that existing between the back electrical contact and (Cd-Zn)S, the Cl-diffused layer is therefore merely a thin skin [52].

CdCl₂ Heat treatment improved the coalescence of nanocrystals from smaller to larger to get better material layers. After CdCl₂ treatment, the grain growth appears collectively with gaps in between grains. This suggested that CdCl₂ treated CdTe film which is produced from Cl precursor has an improved excellence for PV devices because there is no noticeable gaps between the grains, and for less scattering it has larger grain sizes at the boundaries and with high electron mobility [51].

In figure 3(b) also has a rose flower like compact structure but most of the nanoparticles observed distinct and non-uniform around the rose like structure. This result indicates that annealing before CdCl₂ treatment enhances the size of grain in CdTe/(Cd-Zn)S films with recrystallization and occurrence of CdCl₂ encourage a sintering mechanism inside the CdTe film to increase average grain size and decrease intergrain pore size [53].
3.1.3 HRTEM studies

HRTEM is a unique way to access the information at the nanometer (nm) scale. It is also useful for morphological study which provides the shape, size and nanocrystalline behavior. In figure 4 HRTEM images of two types of deposited films (annealed before and after CdCl₂ treatment) are shown. In both the cases micrographs demonstrated the layers consisting of small grains of tens of nm dimensions. A columnar shape is observed in a lot of these grains, which is usual to the substrate of (FTO/(Cd-Zn)S). For fabrication of high efficiency solar cells, there is a need to create the large CdTe grains which is enlarging from (Cd-Zn)S layer to the top surface [50].

The prepared film was treated at 400°C for 2 min that is the optimum temperature and time for obtaining the highest efficiency. Figure 4(a) shows that the HRTEM image has a perfect lattice. There are no stacking faults. No epitaxial co-ordination is observed between the (Cd-Zn)S and CdTe layers. Several types of stacking faults powerfully affect the electrostatic potential within the CdTe grains and act as hole traps, and acquire high stacking fault energies of up to 235 mJ/m² [54]. In figure 4(b), the HRTEM analysis suggests that CdTe grains are epitaxial related to the (Cd-Zn)S grains [also confirmed by high resolution lattice imaging] [55] and they are full of faults and columnar. Selected area electron diffraction (SAED) image shows that the CdTe film has cubic phase, whereas the (Cd-Zn)S film has a combination of cubic and hexagonal phases. The HRTEM images demonstrate thermal grooving on the CdTe surface close to the grain boundaries and independent reformation of the (Cd-Zn)S and CdTe films as a result of the reduction of interfacial energy.
Figure 4. HRTEM images of CdTe/(Cd-Zn)S film: (a) annealed before CdCl₂ treatment (b) annealed after CdCl₂ treatment.

Figure 5 demonstrates the EDX spectrum of CdTe/(Cd-Zn)S film. EDX is a useful tool to identify the available elements present into the composition, product imperfections and defects. It also helps to investigate the failure and identification of cause, catalyst quality, poisoning and elemental distribution.

3.2 Optical Characterizations
3.2.1 Absorbance and transmittance
To develop the PV device, the optical transmission, absorption and the energy band-gap (Eg) of the materials are the essential factors to understand and determine. These parameters analyze the frequency and intensity of the emerging rays. With the help of the optical studies, the colour of an object can be easily identified as it depends on the processes of light emission, transmission and reflection by the object according to the sensitivity of the human eye to the different colours.

Optical absorption spectral studies of CdTe/(Cd-Zn)S/FTO films were performed in the wavelength range of 600 nm - 1000 nm as shown in figure 6. Both the films show high absorbance and less transmittance as the CdTe nature for making better solar devices. But in the absorbance spectra of annealed before CdCl₂ treatment (figure 6(a)) showed little high absorbance than annealed after CdCl₂ treatment (figure 6(b)). The absorption edges are observed to slight shift to lower wavelength side in
case of after CdCl₂ treatment. The optical absorption properties of CdTe improved when grown through process of annealing before CdCl₂ treatment as compared to after CdCl₂ treatment.

Figure 6. Absorption spectra of CdTe/(Cd-Zn)S film: (a) annealed before CdCl₂ treatment (b) annealed after CdCl₂ treatment

In order to determine the energy band-gap of the deposited films, absorption spectra were recorded. With the help of the absorption spectra, energy band-gaps can be easily determined by plotting $(a h \nu)^2$ versus $h \nu$ (Tauc’s plot) by the extrapolation of the linear portion of the curve [56]. The optical direct band-gap values can be determined by the following relation:

$$\alpha(\nu)h \nu = c(h \nu - E_g)^m$$

(2)

Where, $\alpha(\nu)$= absorption coefficient, $E_g$= energy band-gap of the material, $h \nu$= photon energy, $c$= light velocity and $m$= constant value (determined type of optical transition). When the value $m= 1/2$ and 3/2 it is allowed for direct transition, and when $m= 2$ and 3 it is for allowed indirect transitions. In the present case, absorption coefficient ($\alpha(\nu)$) is in the order of $10^4$ cm$^{-1}$ for all the direct band-gap semiconductors [57].

The energy band-gap values are estimated for both the deposited films: annealing before CdCl₂ and after CdCl₂ treated films (figure 7). In energy band-gap value of annealed before CdCl₂ treatment (figure 7(a)) is observed 1.51 eV while in annealed after CdCl₂ treatment (figure 7(b)), the energy band-gap value is 1.49 eV. The slight difference in two films may be attributed to the absorption spectra because there is slight shift in absorption edge. The annealing before CdCl₂ treated film is thinner than the other film so that thin layers generally demonstrate slightly increased band-gap values due to quantum effects and unfinished surface coverage [50].

Figure 7. Estimation of energy band-gap of CdTe/(Cd-Zn)S film using Tauc’s plot: (a) annealed before CdCl₂ treatment (b) annealed after CdCl₂ treatment
For transmission of the light, the scattering and absorption are the two depending factors [58]. The transmittance of a film is complementary to its absorption. The transmittance spectra of CdTe/(Cd-Zn)S/FTO films were recorded in the wavelength range of 600 nm - 1000 nm shown in figure 8. It is observed that in accordance with the high absorption, transmission is less in both the cases. For making solar cell devices, there is a need of high absorption quality and less transmittivity. So, in that way, the film annealed before CdCl$_2$ treatment film is useful for the better productivity of solar cell devices.

![Figure 8. Transmittance spectra of CdTe/(Cd-Zn)S film: (a) annealed before CdCl$_2$ treatment (b) annealed after CdCl$_2$ treatment](image)

### 3.2.2 Photoluminescence studies

PL study is a precise study to investigate the relative energies of the states (ground and excited states), concentrations of the emitting species, and electronic transitions. The electrons release photons with energy corresponding to the material’s energy band-gap in band-to-band transitions. Additionally, photons emit to defect levels from the conduction band (CB), and then defect levels to the valence band (VB). Therefore, peaks can occur under the value of the energy band-gap, but the results can be affected because of the different transitions.

PL spectra of two types of deposited techniques (annealed before CdCl$_2$ treatment and annealed after CdCl$_2$ treatment) are shown in figure 9. The PL spectra observed at an excitation value of 632 nm (1.96 eV). In both the cases band located at ~1.50 eV that can be due to the emission of the defects between the energy levels [59–61]. The existence of defects and particle size distribution may lead to the broadening of the PL spectrum. Broad bands are initiated from the defects in the crystal. The peaks intensities and their FWHM showed nearly identical to the quality of material. Broad peak is observed with high intensity in annealed before CdCl$_2$ treated film (figure 9(a)) demonstrated high crystalline quality, whereas, annealed after CdCl$_2$ treated film has very low intensity (figure 9(b)). This signifies the existence of a huge number of shallow acceptor and donor type defects in the material. Thus, transitions occur from donor to acceptor that produces the photons less than the energy band-gap. In some conditions, where emissions are greater than the energy band-gap values that may be reason of presence of nano-size particles attributing to the quantum confinement effects [62]. The PL spectra of the CdTe/(Cd-Zn)S showed that, although the intensity changed significantly from the center of the grain to the grain boundary but the peak position remained at the same position (~1.50 eV), analogous to the band-gap of the CdTe. The spectra observed from before CdCl$_2$ treatment have large grain and have higher intensities with a peak position at ~1.50 eV and similarly same peak position is observed in after CdCl$_2$ treatment with small grains and low intensity, demonstrating the predominant contribution from lower gap alloys [63].
4. Conclusions

(Cd-Zn)S/CdTe films were deposited onto a FTO substrate by electrodeposition technique. Two types of films were deposited: annealed before CdCl₂ treatment and annealed after CdCl₂ treatment. Structural, optical and morphological properties were investigated. In XRD spectra, the most intense peak at (111) orientation is observed and identified as the zincblende structure. Annealed before CdCl₂ treatment film showed better crystallinity and has large grain sizes. A rose flower-like structure is observed in both the films but in annealed before CdCl₂ treatment film observed better uniformity in crystal and grains. In HRTEM, perfect lattice is observed for the annealed before CdCl₂ treatment film. No epitaxial co-ordination is observed between the (Cd-Zn)S and CdTe layers. Conversely, annealed after CdCl₂ treatment film observed full of faults and epitaxial that may affect the electrostatic potential within the CdTe grains. Annealed before CdCl₂ treatment film has higher absorption quality and less transmittivity which is very suitable for the fabrication of the solar cell devices. The PL spectra of the CdTe/(Cd-Zn)S showed that, although the intensity changed significantly but the peak position remained at the same position (~1.50 eV) which is analogous to the energy band-gap of the CdTe.

References

[1] Hussain K M A, Mahmood Z H, Syed I M, Begum T, Faruque T and Parvin J 2015 *Am. J. Mater. Sci. appl.* 2 91
[2] Hossain M S, Rahman K S, Karim M R, Aijaz M O, Dar M A, Shar M A, Misran H and Amin N 2019 *Sol. Energy* 180, 559
[3] Kasim U, Narayanan H and Anthony O 2008 *Leonardo J. Sci.* 12 111
[4] Kartopu G, Clayton A J, Brooks W S M, Hodgson S D, Barrioz V, Maertens A, Lamb D A and Irvine S J C 2014 *Prog. Photovolt: Res. Appl.* 22 18
[5] Brooks W S M, Irvine S J C, Barrioz V and Clayton A J 2012 *Sol. Energy Mater. Sol. Cells* 101 26
[6] Castillo R H, Acosta M, Riech I, Rodriguez G S, Gamboa J M, Acosta C and Zambrano M 2017 *Optik* 148 95
[7] Osman M A and Abd-Elrahim A G 2018 *Optical Mater.* 77 1
[8] Osman M A, Abd-Elrahim A G and Othman A A 2018 *Mater. Character.* 144 247
[9] Prem Kumar T and Sankaranarayanan K 2009 *Chalcogenide Lett.* 6 617
[10] Lee J H, Song W C, Yang K J and Yoo Y S 2001 *Thin Solid Films* **416** 184
[11] Zhou J, Wu X, Teeter G, To B, Yan Y, Dhere R G and Gessert T A 2004 *Physica Status Solidi B* **241** 775
[12] Werta S Z, Echendu O K, Egbo K O and Dejene F B 2019 *Thin Solid Films* **689** 137511
[13] Rugen-Hankey S L, Clayton A J, Barrioz V, Kartopu G, Irvine S J C, McGettrick J D and Hammond D 2015 *Sol. Energy Mater. Sol. Cells* **136** 213
[14] Yao H, Shen H, Zhu X, Jiao J, Li J and Wang W 2016 *Ceram. Int.* **42** 2466
[15] Kartopu G, Williams B L, Zardetto V, Gurlek A K, Clayton A J, Jones S, Kessels W M M, Creatore M and Irvine S J C 2019 *Sol. Energy Mater. Sol. Cells* **191** 78
[16] Barrioz V, Proskuryakov Y Y, Jones E W, Major J, Irvine S J C, Durose K and Lamb D A 2017 *Mater. Res. Soc. Symposium Proceedings* 1012 Y12
[17] Jones E W, Barrioz V, Irvine S J C and Lamb D 2009 *Thin Solid Films* **517** 2226
[18] Irvine S J C, Barrioz V, Lamb D, Jones E W and Rowlands-Jones R L 2008 *J. Cryst. Growth* **310** 5198
[19] Chavhan S D, Senthilarasu S and Lee S H 2006 Appl. Surf. Sci. **254** 4539
[20] Yamaguchi T, Yamamoto Y, Tanaka T, Demizu Y, Yoshida A, 1996 *Thin Solid Films* **281–282** 375
[21] Noufi R and Zwiebel K 2006 High-efficiency CdTe and CIGS thin-film solar cells: highlights and challenges *In: Proc. 4th World Conf. on Photovoltaic Energy Conversion* 317
[22] Basol B M 1988 *Sol. Cells* **23** 69
[23] Lokhande C D 1990 *Mater. Chem. Phys.* **26** 405
[24] Orton J W, Goldsmith B J, Chapmann J A and Powell M J 1982 *J. Appl. Phys.* **53** 1602
[25] Romeo N, Bosio A, Canevari Vand Seuret D1987 *Sol. Cells* **22** 23
[26] Schaffner J, Feldmeier E, Swirschak U, Schimper H J, Klein A and Jaegermann W 2011 *Thin Solid Films* **519** 7556
[27] Rome N, Bosio A, Canevari V and Podest A 2004 *Sol. Energy* **77** 795
[28] Xu X B, Wang X Y, Gu W P, Quan S and Zang Z 2017 *Superlattices Microstruct.* **109** 463
[29] Archbold M D, Halliday D P, Durose K, Hase T P A, Smyth-Boyle D, and Govender K January 3–7, 2005 Characterization of thin film cadmium sulfide grown using a modified chemical bath deposition process, *in: Proceedings of the Conference Record of the 31st IEEE Photovoltaic Specialists Conference, Coronado Springs Resort Lake Buena Vista, FL* 475
[30] Moutinho H R, Albin D, Yan Y, Dhere R G, Li X, Perkins C, Jiang C S, To B and Al-Jassim M M 2003 *Thin Solid Films* **436** 175
[31] Fritsche J, Kraft D, Thißen A, Mayer T, Klein A and Jaegermann W 2002 *Thin solid Films* **403–404** 252
[32] Wu X, Ribelin R, Dhere R G, Albin D S, Gessert T A, Asher S, Levi D H, Mason A, Moutinho H R and Sheldon P September 15–22, 2000 High-efficiency Cd_{x}SnO_{y}/Zn_{x}SnO_{y}/Znx Cd_{y},S/(Cd-Zn)/CdTe polycrystalline thin-film solar cells, *in: Proceedings of the Conference Record of the 28th IEEE Photovoltaic Specialists Conference, Anchorage 470*
[33] Jaegermann W, Klein A, Fritsche J, Kraft D and Spath B 2005 *Mater. Research Soc. Symposium Proceedings* **865** F6.1
[34] Fritsche J, Klein A and Jaegermann W 2005 *Adv. Eng. Mater.* **7** 914
[35] Lee J H, TextsLee H Y, Park Y K, Shin S H and Park K J 1998 *Jpn. J. Appl. Phys.* **37** 3357
[36] Sanap V B and Pawar B H 2009 *Chelco. Lett.* **6** 415
[37] Luschitz J, Siepchen B, Schaffner J, Lukas-Wollny K, Haindl G, Klein A and Jaegermann W 2009 *Thin Solid Films* **517** 2125
[38] Luschitz J, Lukas-Wollny K, Klein A and Jaegermann W 2007 *Thin Solid Films* **515** 5814
[39] McCandless B E, Moutlon L V and Birkmire R W 1997 *Prog. Photovolt.* **5** 249
[40] Zoppi G, Durose K, Irvine S J C and Barrioz V 2006 *Semicond. Sci. Technol.* **21** 763
[41] Galloway S A and Durose K 1995 SEM/EBIC observations of CdTe/(Cd-Zn)S thin film solar cells Microscopy of Semiconducting Materials (Bristol: Institute of Physics Publishing) 709
[42] Paudel N R, Young M, Roland P J, Ellingson R J, Yan Y and Compaan A D 2014 J. Appl. Phys. 115 064502
[43] Pookparatanana S, Liu X, Paudel N R, Weinhardt L, Bar M, Zhang Y, Ranasinghe A, Khan F, Blum M, Yang W, Compaan A D, and Heske C 2010 Appl. Phys. Lett. 97 172109
[44] Moutinho H R, Al-Jassim M M, Abulfotuh F A, Levi D H, Dippo P C, Dhere R G and Kazmerski L L. 1997 Studies of recrystallization of CdTe thin films after CdCl₂ treatment Proc. 26th IEEE Photovoltaic Specialists Conf. 431
[45] Ferekides C S, Balasubramanian U, Mamazza R, Viswanathan V, Zhao H and Morel D L 2004 Sol. Energy. 77 823
[46] Levi D H, Moutinho H R, Hasoon F A, Keyes B M, Ahrenkiel R K, Al-Jassim M, Kazmerski L L and Birkhire W R 1994 Micro through nanostructure investigations of polycrystalline CdTe: correlations with processing and electronic structures Proc. 24th IEEE Photovoltaic Specialists Conf. 127
[47] Major J D, Bowen L and Durose K 2012 Solar cells Prog. Photovolt. 20 892
[48] Quadros J, Pinto A L, Moutinho H R, Dhere R G and Cruz L R 2008 J. Mater. Sci. 43 573
[49] Lilhare D, Sinha T, Verma L and Khare A 2019 Semicond. Sci. Technol. 34 125010
[50] Dharmadasa I, Madugu M L, Olusola O I, Echendu O K, Fauzi F, Diso D, Weeradinghe, A, Dharmadasa R, Lavery B, Jasinski J B, Kreis, T A and Sumanasekera G 2017 Coatings 7 17
[51] Manaf N A A, Hussein I S, Madugu M L, Olusola O I and Dharmadasa I M 2015 Energies 8 10883
[52] Marfaing Y 2001 Thin Solid Films 387 123
[53] Roh J S and IM H B 1988 Sol. Energy mater. 23 2267
[54] Yoo S H, Butler K T, Soon A, Abbas A, Walls J M and Walsh A 2014 Appl. Phys. Lett. 105 062104
[55] Al-Jassim M M, Hasoon F S, Jones K M, Keyes B M, Matson R J and Moutinho H R 1993 Proc. 23rd IEEE PVSC 459
[56] Tauc J and Menth A 1972 J. Non-Cryst Solids 569 8
[57] Hankare P P, Kokate A V, Asabe M R, Delekere S D and Chouguile B K 2006 Mater. Sci. Eng. B 133 37
[58] Kavitha N, Chandramohan R, Valanarasu S, Vijayan T A, Rex Rosario S and Kathalingam A 2015 J. Mater. Sci: Mater. Electron. 27 2574
[59] Abken A E, Halliday D P and Durose K 2009 J. Appl. Phys. 105 064515
[60] Ahmad-Bitar R N 2000 Renew. Energy 19 579
[61] Vigil O 1997 J. Vac. Sci. Technol. A 15 2282
[62] Glinka Y D, Lin S H, Hwang L P, Chen Y T and Tolk N H 2001 Phys. Rev. B. 64 085421
[63] Dhere R, Rose D, Albin D, Asher S, Al-Jassim M, Cheong H, Swartzlander A, Moutinho H, Coutts T, and Sheldon P October 3, 1997 Presented at the 26th IEEE Photovoltaic Specialists Conference, September 29D Anaheim, California