Investigations on the Physical Properties of CdCl₂ Heat-Treated ITO/CDTE/CDS Thin Films Solar Cell

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Abstract: CdTe/CdS/ITO/glass solar cell was prepared by closed space sublimation (CSS) and chemical bath deposition (CBD). Indium tin oxide (ITO) and tellurium (Te) films were analyzed by spectrophotometry and scanning electron microscopy (SEM). CdTe and CdS thin films were submitted to a chemical treatment at 25°C in a saturated $CdCl_2$ solution (1.04 g/100 mL methanol), followed by heat treatment at 400°C for 30 min. It has been demonstrated that solar cell performance can be improved by depositing a heat-treated $CdCl_2$ layer on the CdTe and CdS layers. The optical, structural and morphological changes of CdTe and CdS surfaces in CdTe/CdS/ITO/glass solar cell, due to $CdCl_2$ solution treatment followed by annealing in air for 400°C were studied using spectrophotometry, XRD and SEM. Optical analysis showed changes in transmittance, refractive index and decrease in thickness and energy band gap after $CdCl_2$ heat-treatment. XRD and SEM results of $CdCl_2$ heat-treated CdTe and CdS thin film samples showed an overall improved crystal structure with progressive increase in crystallite and grain size.

Key words: $CdCl_2$ · Cadmium sulfide · Cadmium telluride · Heat treatment · Morphological · Optical · Structural.

INTRODUCTION

Considering the high absorption coefficient, near optimum band gap and manufacturability of CdTe, it can quite easily be regarded as one of the most favorable photovoltaic materials realizable for use as high-efficiency and low-cost thin film solar cell [1- 4]. Typically, a CdTe solar cell structure consists of Au/CdTe/CdS/ITO/glass. The hetero-interface is known to limit the performance of solar cell efficiency.

The general working and properties of solar cells can be best described by three parameters; short circuit current (I_{SC}), open circuit voltage (V_{OC}) and fill factor (FF). Post-deposition processing of polycrystalline CdTe/CdS hetero-junction thin film solar cells with cadmium chloride ($CdCl_2$) heat-treatment has proved to improve the short circuit current and open circuit voltage of CdTe/CdS thin film solar cell, by recrystallization, reorientation and grain enhancement of films for photovoltaic operation [5-7].

Heat treatment with $CdCl_2$ has been known to be a key step in high-quality CdTe/CdS thin film solar cell preparation [7-11]. Irrespective of the method being used for deposition of CdTe and CdS layer, $CdCl_2$ treatment has become a customary and vital process in fabrication of high-efficiency CdTe/CdS based photovoltaic devices. Three different methods of $CdCl_2$ treatment are widely known to be used; solution $CdCl_2$ treatment, evaporated $CdCl_2$ treatment and vapor $CdCl_2$ treatment [12]. $CdCl_2$ treatment is basically known to activate a chemical reaction between CdTe and CdS, which is the driving force for the bulk and grain-boundary inter-diffusion of CdTe and CdS[13]. However, regardless of the $CdCl_2$ treatment method being used, the basic mechanism by which $CdCl_2$ effects CdTe and CdS can be expected as a similar process [7, 13-15].

The optical, structural and morphological properties of CdTe and CdS thin films are mainly subjective to the preparation route. Hence, a variety of methods have been

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applied for the synthesis of such materials e.g. thermal evaporation, chemical pyrolysis deposition (CPD) [16], metal organic chemical-vapor deposition (MOCVD) [17-19], closed space sublimation (CSS) [16, 20] and chemical bath deposition (CBD) [16, 21-23]. CSS and CBD are known to produce optimal and encouraging results for CdTe/CdS based solar cells. Both the techniques have many advantages for production of photovoltaic devices under controlled conditions, such as exceptional uniformity and reproducibility of film thickness even for a large-scale module [2, 24, 25].

In the present work, effects of $CdCl_2$ thermal treatment on physical properties of CdTe/CdS hetero-junction solar cells, fabricated using CSS and CBD, have been investigated. Correspondingly, the results have demonstrated that performance of solar cell can be improved significantly after this treatment. In this regard, optical properties such as film thickness, refractive index, absorption and optical band gap, crystallographic properties such as crystallite size and plane orientation and morphological properties such as grain size have been investigated using UV-VIS-IR spectrophotometer, X-ray diffraction (XRD) and scanning electron microscopy (SEM) respectively, at room temperature (25°C) [2, 26, 27].

Experimental: CdS thin films were deposited on ITO glass substrate by CBD technique using $CdCl_2$, ammonium nitrate (NH_4NO_3), potassium hydroxide (KOH) and thiourea as starting materials. ITO coated glass was used as available from Sigma-Aldrich. Deposition was carried out with magnetic stirring at 3 Hz for 30 min at 75°C. The resulting CdS layer was annealed at 400°C for 30 min in a vacuum chamber at $4x10^{-2}$ mbar and its thickness was found to be about 200 nm. The CdTe layer was deposited on CdS by CSS technique under vacuum of $4x10^{-1}$ mbar. Deposition time was kept as 3-5 min. The substrate and source temperature were maintained at 400°C and 530°C respectively. A 500 W halogen lamp was used to heat the CdS/ITO/glass substrate, whereas a graphite boat was used to heat the source material with a 1000 W halogen lamp. The source and substrate spacing was measured as 4-5 mm. CdTe film thickness was measured as 1.5 μm. To enhance the p-type properties of CdTe, tellurium (Te) layer (500 nm) was deposited on CdTe by CSS technique under vacuum of $4x10^{-2}$ mbar. Deposition time was kept as 5 min, whereas, source and substrate temperatures were kept as 350°C and 200°C respectively. Resulting Te layer was annealed at 200°C for 1 hour.
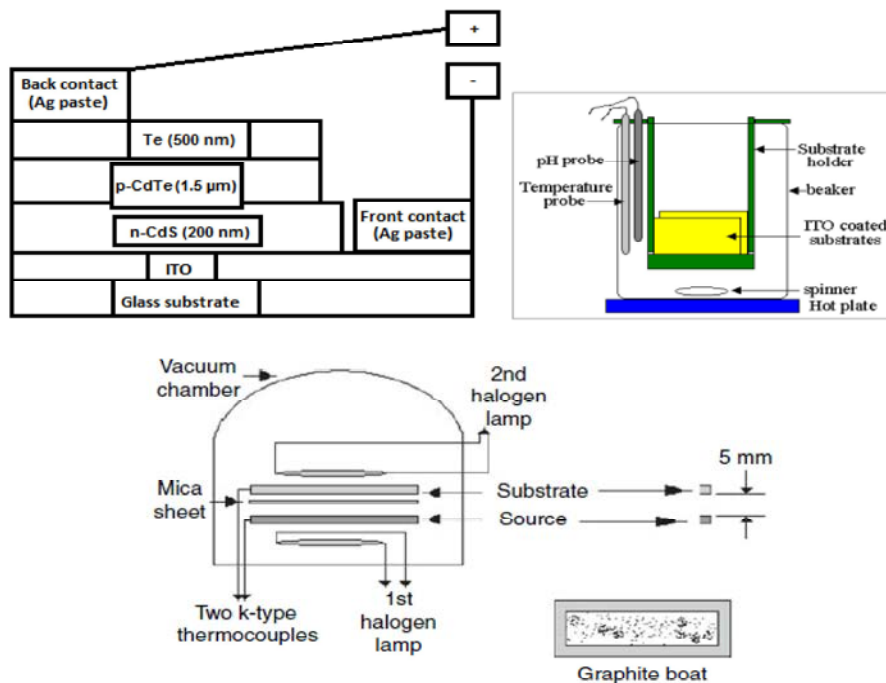

Fig. 1: (a)Configuration of ITO/CdTe/CdS hetero-junction solar cell structure used in the present work.(b) Chemical bath deposition system used for preparation of CdS layer. (c) Closed space sublimation system used for preparation of CdTe layer.

1.04 g $CdCl_2$ was dissolved in 50 ml methanol at 65°C with constant magnetic stirring at 3 Hz for 10 min. $CdCl_2$/methanol solution was then allowed to cool down at room temperature (25°C). The CdS/ITO/glass and the CdTe/CdS/ITO/glass structures were soaked in the $CdCl_2$ solution for 7 sec. After drying at room temperature, the structures were annealed in a tube furnace for 30 min at 400°C with constant flow of argon gas (30 ml/min).

Transmission spectra, X-ray diffraction (XRD) and scanning electron microscope (SEM) with Energy Dispersive X-Ray (EDX) investigations were carried out in order to understand the optical, crystallographic and morphological effects of $CdCl_2$ treatment on CdTe and CdS films. Optical analysis using UV-VIS-NIR Spectrophotometer was also used to study the thickness of films. Rutherford back scattering (RBS) analysis was used to identify the elemental composition of CdS thin films and further confirm their thickness. Rutherford back scattering spectrometry with an accuracy of 7% was used. High energy alpha particles were bombarded on the CDs film. Backscattered He^{2+} ions energy distribution and yield at a given angle was measured. Backscattered ions were detected by using a surface barrier detector with 17 keV resolution kept at a scattering angle of 160°. Since cross section of backscattering for each element is known, it is possible to get a quantitative compositional analysis from the RBS spectrum.

Silver (Ag) paste annealed in a tube furnace at 100°C for 1 hour was used for ohmic contact formation in the ITO/CdS/CdTe solar cells structure as shown in Fig. 1(a). Chemical bath deposition (CBD) and closed space sublimation (CSS) setups used for the fabrication of solar cell are shown in Fig. 1(b) and Fig. 1(c) respectively.

RESULTS AND DISCUSSIONS

Analysis of ITO Layer: Indium Tin Oxide (ITO) is a heavily doped n-type semiconductor with a large band gap of around 4 eV. It is typically used as the transparent conducting oxide (TCO) layer in fabrication of solar cells and is well-known for its high transmittance. Transmittance of ITO glass was investigated using PerkinElmer ultraviolet-visible-infrared (UV-VIS-IR) spectrophotometer ranging from 250 - 2250 nm. Transmission of more than 95 % for the whole wavelength is demonstrated, as shown in Fig. 2(a). Surface morphology of ITO was studied using scanning electron microscopy (SEM). SEM image in Fig. 2(b) shows a slightly rough surface with an average grain size of about 80 nm.
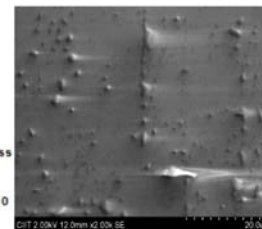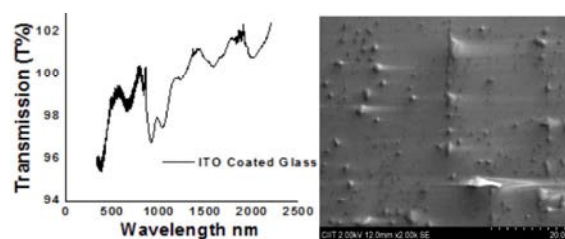
(a)   (b)

Fig. 2: (a) Transmission spectra of ITO thin film. (b) SEM image of ITO thin film.
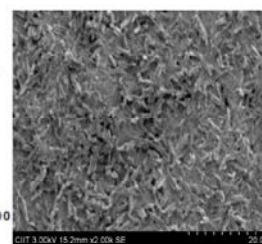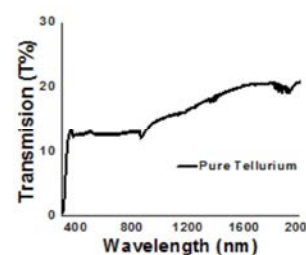
(a)   (b)

Fig. 3: (a) Transmission spectra of Te thin film (annealed at 200°C). (b) SEM image of Te thin film (annealed at 200°C).

Analysis of Te Layer: Thin film of pure tellurium (Te) was deposited on CdTe to increase the p-type properties of CdTe. Closed space sublimation (CSS) technique was used for the deposition. Sigma Aldrich (99.999%) tellurium powder was used as source material. Transmittance of Te layer was investigated using Perkin Elmer ultraviolet-visible-infrared (UV-VIS-IR) spectrophotometer ranging from 250 - 2250 nm. Thickness of Te was calculated as 500. Transmission of up to 15 % in visible region and 20% in IR region is demonstrated, as shown in Fig. 3(a). Surface morphology of Te was studied using SEM. Results in Fig. 3(b) show a slightly rough Te surface with an average grain size of about 300 nm.

Analysis of CdTe Layer and $CdCl_2$ Heat-Treatment Effects
Optical Analysis of CdTe Layer: Optical measurements using spectrophotometer can provide information about transmittance, thickness, refractive index, absorption coefficient and energy band gap. The as-deposited and $CdCl_2$ heat-treated CdTe thin films show high absorption in the visible and near-infrared regions. Due to roughness, transmission in the as-deposited sample is about 60% at

higher wavelength, which decreases to about 55% in the $CdCl_2$ heat-treated sample in higher wavelength region.

Refractive index 'n' and thickness 'd' can be calculated easily from transmission measurements using a simple method developed by Manifacier et al [26]. Thickness 'd' of the film can be determined from two maxima or minima using Eq. (1).

$$d = \frac{M(\lambda_{max}\lambda_{min})}{4n(\lambda_{max} - \lambda_{min})} \quad (1)$$

Where, M is the number of oscillations between maximum and minimum transmission wavelengths 'λ_{max}' and 'λ_{min}', respectively. 'n' can be calculated using the relation:

$$n = \sqrt{\frac{[N + (N^2 - 4s^2)^{\frac{1}{2}}]}{2}} \quad (2)$$

Where,

$$N = 1 + s^2 + 4s\left(\frac{T_{max} - T_{min}}{T_{max} * T_{min}}\right) \quad (3)$$

Here, the refractive index of glass, $s = 1.52$, 'T_{max}' and 'T_{min}' are the maximum and minimum transmissions, respectively. The values of 'd' and 'n' are calculated from Eq. (1) and (2). The standard transmittance 'T' for thin film on transparent substrate surrounded by air is n = 1. The optical properties demonstrate a slight increase in absorption in IR region. Consequently, the transmittance is seen to slightly decrease after $CdCl_2$ heat-treatment, as shown in Fig. 4. The thickness and refractive index of as-deposited CdTe thin film sample were calculated as 1.4 µm and 2.21 respectively. After $CdCl_2$ heat-treatment, the thickness decreased to 1.335 µm, however, there was no change in the refractive index. Decrease in thickness is beneficial since it facilitates rise in open circuit voltage of solar cell. The band gap can be determined using the following relation:

$$ahv = A(hv - E_g)^{N/2} \quad (4)$$

Here 'A' is a constant, 'hv' is the photon energy, 'E_g' is the optical energy band gap. 'N' depends on the nature of the transition (N = 1 for direct band gap, while N = 4 for indirect band gap transition). 'hv' can be calculated by:
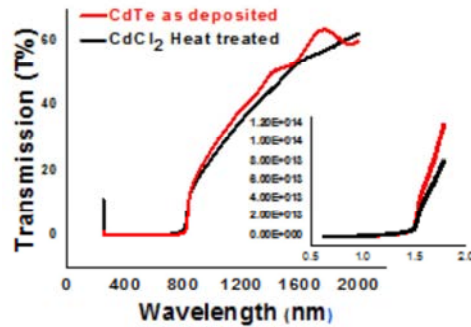
$$hv(eV) = 1.24/\lambda(\mu m) \quad (5)$$

Fig. 4: Transmittance spectra of as-deposited and $CdCl^2$ heat-treated CdTe samples. Inset: Plot of $(ahv)^2$ as a function of hv for as-deposited and $CdCl^2$ heat-treated CdTe samples.

The absorption co-efficient can be calculated as:

$$\alpha = \frac{1}{d}\ln(\frac{1}{T}) \quad (6)$$

A high absorption coefficient is vital from both economic and technological point of view. Large absorption coefficient permits the use of a relatively thinner absorber layer. Hence, lesser material is required for device fabrication. Optical measurement results show high absorption which matches well with the solar spectrum, henceforth confirming these CdTe films to be optically suitable for use as absorber in solar cells. The band gap can be obtained by extrapolating $(áhv)^2vs.$ the incident photon energy (hv) plot. Inset of Fig. 4 shows the energy band gap values of the as-deposited and $CdCl_2$ heat-treated samples. The band gap values extracted from these plots are 1.47 eV for as-deposited and 1.43 eV for $CdCl_2$ heat-treated sample. Results of optical measurements after $CdCl_2$ heat-treatment show a slight decrease in band gap values, indicating towards enhancement in transmission, which is beneficial for enhancement in efficiency of CdTe as absorber layer in CdTe/CdS solar cell.

Structural Analysis of CdTe Layer: The crystallographic orientation of CdTe thin film samples was studied using X-ray diffraction (XRD) analysis, as illustrated in Fig. 5. The main reflections of the samples are the same and can be indexed according to fccCdTe lattice. The data analysis gave the lattice constant as 6.50 Å for the as-deposited and $CdCl_2$ heat-treated samples, which agreed with the
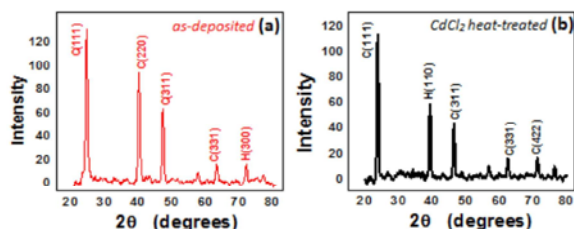
Fig. 5: XRD traces of CdTe(a) as-deposited (b) after CdCl₂ heat-treatment.

Fig. 6: SEM images of (a) as-deposited CdTe sample (b) CdCl₂ heat-treated CdTe sample.

reported value of 6.410 Å of lattice constant [29, 30] (ASTM Cards 15-0770, 75-2086). The strongest (111) reflection in the samples indicate the preferential orientation. However, the intensity of (111) peak is slightly lower in CdCl₂ heat-treated sample. The decrease in the level of intensity after CdCl₂ heat-treatment indicates towards a better crystalline quality [31]. Similarly the (220) peak has vanished in the CdCl₂ heat-treated sample and a new peak (110) of hexagonal structure has appeared. No significant change in the diffraction angle of CdCl₂ heat-treated sample was seen. The change in peak position is due to lattice stress [32]. The crystallite size can be calculated with the help of Scherrer formula:

$$D = \frac{0.9\lambda}{B\cos\theta} \qquad (7)$$

Where, 'λ' is wavelength of X-rays, 'θ' is angle of diffraction (Bragg's angle) and 'B' is full width at half maximum (FWHM) [33, 34]. The dislocation density is calculated using $1/D^2$[32]. The crystallite size of as-deposited CdTe thin film was 258.17 Å, which increased to 295.05 Å after CdCl₂ heat-treatment, resulting in a decrease in dislocation density, which may be attributed to improvement of the crystal structure. In principle, the Cd atoms of CdCl₂ combine preferentially with the Te atoms at the CdTe surface, causing recrystallization and reorientation. Table 1 shows the 2θ diffraction angle value of strongest peak, FWHM and crystalline size of CdTe as-deposited and CdCl₂ heat-treated samples.

Surface Morphology of CdTe layer: The surface morphology of CdTe as-deposited and CdCl₂ heat-treated samples was studied using scanning electron microscopy (SEM). Results are shown in Fig. 6. Changes in the shape and size of CdTe grains were observed. Average grain size of the as-deposited sample was about 0.50 μm, as shown in Fig. 6(a), which improved to about 0.70 μm after
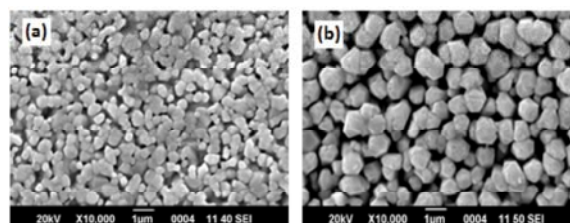
Table 1: 2θ diffraction angle, full width at half maxima (FWHM) and crystalline size of CdTe as-deposited and CdCl₂ heat-treated samples.

CdTe	2θ	FWHM	Crystalline size (Å)
As-deposited	23.81°	0.31	258.17
CdCl₂ heat-treated	23.77°	0.27	295.05

CdCl₂ heat-treatment, as shown in Fig. 6(b). The grain size of the CdCl₂ heat-treated sample is much larger than that of the as-deposited sample. In principle, CdCl₂ heat-treatment re-crystallizes the CdTe layer. Smaller grains coalesce together, whereas, some of the bigger grains divide into smaller grains and reorient themselves, which affects the overall microstructure [35, 36]. The re-crystallizations of grain's growth in II-VI semiconductors are reported comprehensively [34]. SEM image also shows that roughness is reduced after CdCl₂ heat-treatment. The SEM results thoroughly support the XRD results.

The composition of Cd and Te in the CdTe as-deposited sample was measured with the help of energy dispersive X-ray (EDX) spectroscopy attached to the SEM. As shown in Fig. 7, the Cd peaks at 3.2 keV and 3.35 KeV and the Te peaks at 2.2 KeV, 3.5 KeV, 3.5 KeV, 3.7 KeV, 4.1 KeV, 4.4 KeV, 4.6 KeV and 4.75 KeV in EDX spectrum indicate the existence of Cd and Te in the as-deposited CdTe film, in a concentration of 47.18 and 52.82 mass%.

Analysis of CdS Layer and CdCl₂ Heat-Treatment Effects
Optical Analysis of CdS layer: Optical measurements of the as-deposited and CdCl₂ heat-treated CdS thin films were performed by taking transmission spectrum using spectrophotometer. Optical spectra of CdS as-deposited sample exhibited high transmission from 60% to 80% in infrared and visible region, with a steep edge at about 500 nm wavelength, as shown in Fig. 8. The thickness and refractive index of thin films can be calculated by the Swanepoel model [37], using Eq. (1) and (2) respectively. The number of oscillations 'N' and band gap can be
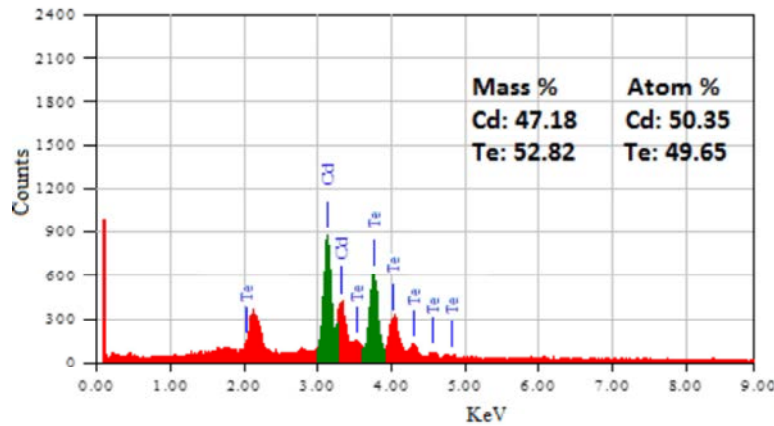
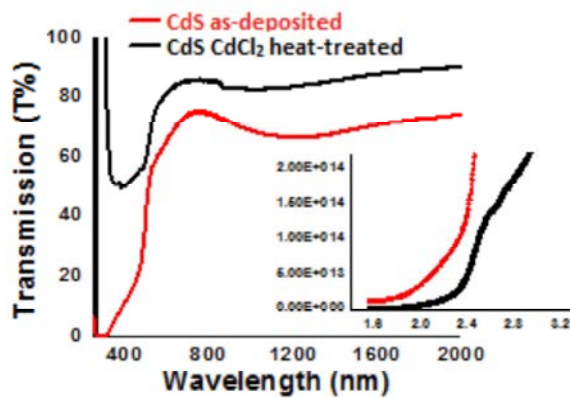Fig. 7: Energy Dispersive X-Ray (EDX) image of as-deposited CdTe sample

Fig. 8: Transmittance spectra of as-deposited and CdCl$_2$ heat-treated CdS samples. Inset: Plot of (ahv)^2 as a function of hv for as-deposited and CdCl$_2$ heat-treated CdS samples.

Fig. 9: XRD traces of (a) as-deposited CdS sample (b) CdCl2 heat-treated CdS sample.

calculated using Eq. (3) and (4) respectively. Thickness of the as-deposited CdS thin film sample was calculated as 200 nm, which decreased significantly to 70 nm after CdCl$_2$ heat-treatment. The refractive index of the as-deposited CdS thin film sample was calculated as 2.27, which rose to 2.85 after CdCl$_2$ heat-treatment. The significant decrease in film thickness is highly beneficial for rise in the open circuit voltage of solar cell.

CDs thin film is highly transparent in the visible region. The absorption of the film in transparent region could be due to light scattering, defect absorption, multi-phonon absorption, or Urbach tail [38]. The absorption co-efficient can be calculated using Eq. (6). By extrapolating (áhv)^{2}vs. the incident photon energy (hv) plot, the energy band gap (inset of Fig. 7) can be calculated. After CdCl$_2$ heat-treatment, about (10-15) %
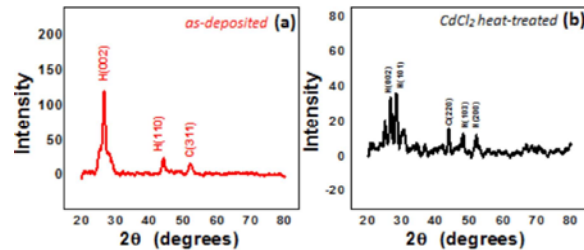
increase in transmittance is seen. Similarly, band gap is seen to reduce from 2.336 eV to 2.286 eV, after CdCl$_2$ heat-treatment, which indicates enhancement of transmission, which is beneficial for enhancement in efficiency of CdS as window layer in CdTe/CdS solar cell. The variation in band gap of CdS thin films may be attributed to lattice strain [39].

Structural Analysis of CdS Layer: The structural characterization of cadmium sulfide thin films was performed by XRD with a wavelength 1.5406 Å in the diffraction angle ranging from 20° to 80°. Results are illustrated in Fig. 9. Peaks relating to CdS are identified using standard card JCPDS-00-041-1049. Cadmium sulfide has hexagonal structure with effective parameters a = b = 4.1409Å, c = 6.7198Å.

The preferred orientation of CdS as-deposited is represented by (002) hexagonal peak. After CdCl$_2$ heat-treatment, the (002) peak shifted to a lower diffraction angle, whereas, the hexagonal peak (101) indicated the preferred orientation. The hexagonal phase of CdS thin films revealed the general tendency that c-axis of CdS is perpendicular to the film surface [40]. The diffraction

angle 26.59° of strongest (002) peak of as-deposited sample shifted towards higher 2θ value (28.28°) in strongest (101) peak of $CdCl_2$ heat-treated sample, which confirmed decrease in (002) lattice constant. The lower angle in the as-deposited sample is due to residual strain, whereas, the change in peak position is due to lattice stress [32]. The intensity of strongest (101) peak in $CdCl_2$ heat-treated sample is significantly lower as compared to the strongest (102) peak of as-deposited sample. This decrease in the level of intensity after $CdCl_2$ heat-treatment points towards a better crystalline quality [31].

The crystallite size (CS) can be calculated with the help of Scherrer formula, using Eq. (7). The dislocation density is calculated using $1/D^2$[32, 41]. The crystallite size of as-deposited CdS thin film is 207.07 Å, which increased to 259.57 Å after $CdCl_2$ heat-treatment. As a result, the dislocation density decreased after $CdCl_2$ heat-treatment, which may be attributed to improvement of the crystal structure. An increase in the quantity of peaks is also seen after $CdCl_2$ heat-treatment. Shift in the diffraction angle of strongest peak, change in crystallite size, decrease in intensity of preferred orientation and increase in the number of peaks confirms that annealing the $CdCl_2$ treated CdS film at 400°C promotes the combination of the Cd atoms of $CdCl_2$ preferentially with the S atoms of CdS, hence, aiding to the recrystallization and reorientation. Table 2 shows the 2θ diffraction angle values, FWHM and crystallite size for CdS as-deposited and $CdCl_2$ heat-treated sample.

Surface Morphology of CdS Layer: The scanning electron microscopic (SEM) images of as-deposited CdS and $CdCl_2$ heat-treated CdS samples are shown in Fig. 10. Grain size of CdS is typically dependent on the annealing temperature. As-deposited CdS sample was found to have a grain size of about 300 nm, which reached to 500 nm after $CdCl_2$ heat-treatment. $CdCl_2$ was diffused into the CdS sample, hence improving the grain size of $CdCl_2$ heat-treated sample. The annealing temperature facilitates $CdCl_2$ to diffuse and reorient the microstructure, as evident in the XRD pattern. SEM images and XRD results clearly exhibit increase in grain and crystallite size after $CdCl_2$ heat-treatment.

The RBS spectrum of the as-deposited CdS film is shown in Fig. 11. Two prominent peaks corresponding to Cd and S are seen. The thickness of CdS (200 nm) measured from RBS agrees with the value measured by optical analysis using UV-VIS-NIR Spectrophotometer. At higher temperatures, during sublimation, the CDs
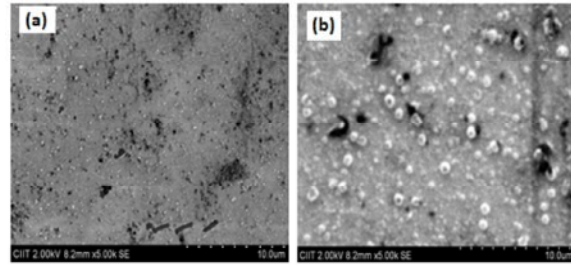

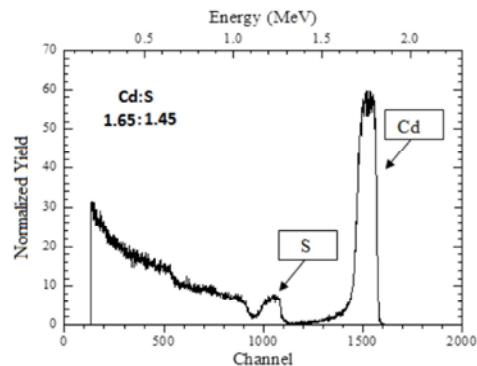Fig. 10: SEM images of (a) as-deposited CdS sample (b) $CdCl_2$ heat-treated CdS sample.

Fig. 11: Rutherford back scattering (RBS) spectrum of the as-deposited CdS sample.

Table 2: 2θ diffraction angle, full width at half maxima (FWHM) and crystalline size of CdS as-deposited and $CdCl_2$ heat-treated samples.

CdS	2θ	FWHM	Crystalline size (Å)
As-deposited	26.59°	0.39	207.07
$CdCl_2$ heat-treated	28.28°	0.31	259.57

compound dissociates itself into Cd and S. Chemical bonding again takes place, at substrate temperature and CdS compound is again formed. Elemental composition of the as-deposited CdS thin film is shown in the RBS plot in Fig. 10. CdS is present with Cd to S ratio of 1.65 to 1.45.

CONCLUSIONS

ITO/CdTe/CdS/glass solar cell was successfully prepared using CSS and CBD techniques. Optical analysis of ITO demonstrated transmittance of over 95% for whole wavelength, whereas in case of Te layer, transmittance of about 20 % in IR region was observed. SEM images of ITO and Te layer showed grain sizes of about 80 nm and 300 nm respectively. EDX and RBS analysis facilitated in studying the elemental composition of as-deposited CdTe and CdS thin films. The Cd and Te concentration in the

as-deposited CdTe sample was found to be about 47.18% and 52.82%, whereas, Cd and S in the as-deposited CdS sample was found to be in the ratio of 1.65 to 1.45 respectively. The effects of $CdCl_2$ immersion and heating on the optical, structural and morphological properties of CdTe and CdS surfaces were studied with an effort to promote transmission enhancement, recrystallization and reorientation, thereby, improving the overall crystal structure, crystalline quality and surface morphology.

Optical results of CdS showed an increase in refractive index, whereas, the thickness of both CdTe and CdS thin films decreased after $CdCl_2$ heat-treatment. The decrease in thickness is highly beneficial for enhancement of solar cell efficiency, since, lower the thickness, higher the open circuit voltage. Similarly, a decrease in energy band gap was demonstrated, which may be attributed to the enhancement of transmission. Structural properties investigated with the help of XRD exhibited shift in 2θ diffraction angles of strongest peaks, increase in crystallite size, decrease in dislocation density and decrease in intensity of strongest peak and change in the total number of peaks. The shift of 2θ diffraction angle was insignificant in case of CdTe film, whereas, a significant shift to a higher 2θ diffraction angle value was observed for CdS film, after $CdCl_2$ heat-treatment. Decrease in intensity of strongest peaks for both CdTe and CdS thin films, after $CdCl_2$ heat-treatment, were prominent, indicating towards improved crystalline quality. Similarly, an increase in crystallite size and a consequent decrease in dislocation density, after $CdCl_2$ heat-treatment, pointed towards improvement in overall crystal structure. These results confirmed improvement in efficiency of CdTe and CdS films as absorber and window layer for CdTe/CdS photovoltaic operations. Surface morphology of both CdTe and CdS thin films was affected by $CdCl_2$ heat-treatment as well. SEM images assisted in investigating the changes. Grain size of CdTe as-deposited sample (0.50 μm) was found to improve to 0.70 μm after $CdCl_2$ heat-treatment. Similarly, grain size of CdS as-deposited sample (0.30 μm) was found to improve to 0.50 μm after $CdCl_2$ heat-treatment.

In conclusion, significant improvement to the CdTe/CdS films solar cell performance can be achieved when annealed at 400°C in the presence of $CdCl_2$ on the free surfaces of CdTe and CdS. These results can be further used to improve the efficiency of CdTe/CdS hetero-junction solar cell.

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