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Close-Spaced Sublimation (CSS): A Low-Cost, High-Yield Deposition System for Cadmium Telluride (CdTe) Thin Film Solar Cells

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Abstract

Semiconductors are the key materials in many of our modern day devices, such as sensors, integrated circuits, energy harvesting devices, optoelectronics and so on. However, apart from two known elemental semiconductors that are silicon and germanium, we have been using many of the synthesized ones since the microelectronic revolution known as invention of transistor. Numerous compound semiconductors since then have been synthesized, grown, deposited or simply fabricated by numerous processes in the scientific community. To avoid associated chemical disposals or keep safe from toxic or combustible gas usages in any semiconductor fabrication facilities, many researchers choose physical vapor deposition as the simplest method. One of such processes is called Close-Spaced Sublimation (CSS), which is a kind of thermal evaporation by nature. This chapter would give a comprehensive outline on CSS as one of the most advantageous semiconductor deposition processes for many compound semiconductors having relatively low evaporation temperature. Cadmium telluride (CdTe) is one of the examples utilized for solar cell absorber materials since the early 1980s using CSS technique. Therefore, growth of CdTe thin films by CSS and its utilization in thin film solar cells will be discussed to comprehend the ultimate benefits of the close-spaced sublimation (CSS) process.

Keywords: semiconductors, thin films, close-spaced sublimation, temperature profile, CdTe thin film solar cells

1. Introduction

Close-spaced sublimation (CSS) is one of the simplest methods in physical vapor deposition. Materials especially semiconductors that evaporate below 800°C can be coated on substrates like glass in both vacuum and atmospheric pressure. The target materials have to be in the form of solid in either chunk or powder form [1–3]. As for example, compound semiconductor like cadmium telluride (CdTe) can be deposited at around 600°C with a thickness of 1–10 μm within 10 min of deposition time, which is one of the fastest deposition times among other physical vapor deposition (PVD) methods. Needless to mention, CSS and binary compound material cadmium telluride (CdTe) are densely interrelated due to extensive usage of CSS in the growth of CdTe thin film [4, 5]. The binary compound CdTe has been recognized as one of the promising thin film photovoltaic materials owing to its near optimum bandgap of 1.44 eV and high absorption coefficient over 10⁵/cm. CdTe, therefore, absorbs over 90% of available photons ($h\nu > 1.44$ eV) in 1 μm thickness, and hence, films of only 1–3 μm are sufficient for solar cells [6, 7]. Several types of CdTe solar cells such as Schottky barrier, homojunction, heterojunction, and p-i-n have been investigated to date [8–10]. Among all, the most successful configurations are the heterojunctions where a wide bandgap semiconductor can be used as the heterojunction partner or “window.” However, cadmium sulfide (CdS) has been the most widely studied and most appropriate window material for CdTe solar cells to date. Most recent development in CdTe thin film solar cells has found noteworthy improvements in small area conversion efficiencies. A number of techniques such as atomic layer epitaxy, spraying, electrodeposition (ED), and close-spaced sublimation (CSS) have been employed for the fabrication of CdTe thin film solar cells with significant efficiencies of over 20% with various configurations. It is quite notable that even though important dissimilarities exist, the performances achieved are independent to processing demonstrating the versatility of CdTe and its superior status in the photovoltaic technologies.

The deposition method for CdTe thin films differs widely and can considerably affect the material properties and device performance. Since CdTe has high absorption coefficient hence thicknesses for CdTe thin films are limited within 2–10 μm [11, 12]. There are various methods to deposit CdTe, which includes close-spaced sublimation (CSS), vapor transport deposition (VTD), electrodeposition (ED), physical vapor deposition (PVD), sputtering, etc. [13–15]. Among all the deposition methods, the highest efficient CdTe thin film solar cell was obtained by close-spaced sublimation (CSS). The substrate temperature is one of the crucial parameters for CdTe deposition as it could be observed that most of the deposition techniques demonstrated has substrate heating. Higher growth temperature not only enhances the deposition rate, but it also determines the quality of junction formation. Moreover, some research studies illustrated that CdTe deposited at higher temperature exhibits better performance. Therefore, the resistivity of the CdTe films decreases with an increase in substrate temperature.

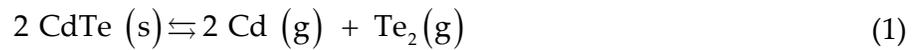
2. Deposition of CdTe thin films by close-spaced sublimation (CSS) technique

The CSS technique is particularly attractive for the deposition of CdTe films since it offers high deposition rates and can be simply scaled up for manufacturing purposes. CSS equipment can be constructed with a wide variety of options such as vacuum, temperature, spacing between source and substrate. One can design first based on required material to be coated on substrates. As for example, the source and substrate in case of CdTe are kept at a close distance of 2 mm in our case, which can also be changed by some simple techniques like increasing spacer of certain thickness. Now, top and bottom heaters can be chosen according to the temperature needed to evaporate either in atmospheric pressure or evacuating to the range of millitorr, filling with certain gas like Ar or N₂. There is a need for good temperature controller which can be programmable in steps such as increment or hold time. Finally, natural cooling is followed to let the temperature falls back to room temperature. Interestingly, the whole CSS deposition takes place within only 10 min, excluding the evacuation or purging time. We have successfully grown a required thickness of 1 micron for CdTe to be used in solar cells, which is the most challenging part in CSS to learn temperature profiles for various thickness with the best coating or film properties needed in each application.

The main design prerequisite for the close-spaced sublimation (CSS) equipment is to minimize the influence of extrinsic impurities that could be incorporated from ambient to the deposited films. This requirement minimizes the number of impurity sources that would be heated to high temperatures together with the number of wires required to feed through the chamber. Sublimation illustrates the direct phase transition between a solid and gas state. A close-spaced sublimation is dependent on the following factors:

- Sublimation process at the surface of the source
- Transport of the gas from the source to the substrate surface
- Sublimation process at the surface of the substrate

Phase diagrams of CdTe demonstrate a very narrow composition where the CdTe binary compound exists as a solid without any other phases, with an atomic percentage of tellurium equal to approximately 50%. The melting point of the material is also a maximum at this point and equal to 1099°C [16]. Greenberg calculated the range of tellurium concentration over which the material is in a purely solid phase to be 49.996 to 50.012 atomic percent [17]. A pressure phase temperature diagram of CdTe has also been published, which indicates the boundary of a solid to vapor transition [18]. The sublimation of CdTe occurs in the region where the CdTe is in a pure solid phase as calculated by Greenberg. This region is defined by the solid-liquid-vapor transition as the upper limit, the sides are defined by the limits of Cd and Te saturation in CdTe, and the bottom is defined by the line of stoichiometric congruent sublimation where the vapor has the same composition as the solid [19]. The sublimation reaction happens in the following equation [20]:



The consequence of manipulating certain deposition parameters on the growth rate has also been reported earlier. Alamri demonstrated two distinct growth rate regions when increasing the source and substrate distance for a series of depositions [21]. This would specify a change in the growth mechanism, apparently from a sublimation limited to diffusion limited case. The growth rate was found to be independent of the substrate temperature (over a 100°C region), for temperatures significantly lower than source temperature and with a low deposition chamber pressure (10^{-5} mbar). This result does not emerge to agree with the theory for any sublimation limited cases suggested by others groups. No reason for this disagreement can be found from the experimental detail provided. As the distance between the source and substrate increased at low pressures, the growth rate was reported to decrease due to the divergence of the gas. Research works by Nagayoshi and Suzuki observed that the deposition rate increased as the source temperature increased for a deposition under vacuum, in agreement with a sublimation limited case [22]. They also varied the substrate temperature showing for a source temperature of 650°C and a substrate temperature of 520°C, the growth rate reached maximum in that case. The incidence of a maximum deposition rate for a series of experiments where only the substrate temperature was varied would imply varying this parameter changed the deposition mechanism. Work by Anthony et al. showed the composition of the environment gas also has an effect on the diffusion limited process. They recommend that the faster growth rate in a helium environment compared to argon was due to the small molecular weight and diameter of the helium [23].

2.1. Close-spaced sublimation (CSS) system

CSS technique has been mainly emphasized for the deposition of CdTe films on foreign substrates. This technique has been extensively investigated because of the relatively high efficiency of solar cells prepared from CSS grown CdTe films. Deposition by reaction condensation from vapor generated from direct sublimation of the compounds has produced the highest efficiency devices. A schematic diagram of the CSS apparatus is shown in **Figure 1**.

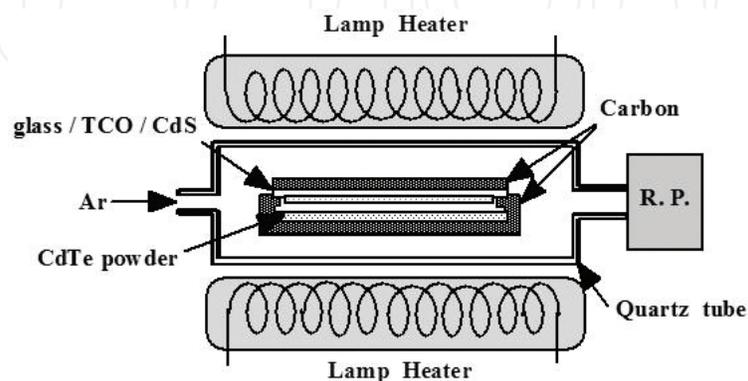


Figure 1. Schematic view of close-spaced sublimation (CSS) apparatus.

The substrate and source, separated by a small distance (1 mm for instance) and placed on appropriate holders, are enclosed in a fused silica tube with gas inlet and outlet tubes to keep controlled environment inside. The system is maintained at desired temperatures by using infrared radiation, and thermocouples inserted into the sample holders are used to monitor their temperatures. The important process parameters are the temperatures of the source and the substrate, the nature of the atmosphere, the pressure in the reaction tube, and the composition of the source material. These parameters are inter-related. For example, the partial pressure of Cd and Te₂ in the reaction tube is important in determining the rate of deposition, and these pressures, or the dissociation pressure of CdTe, depend exponentially on temperature. At a given source temperature, the sublimation rate increases rapidly as the pressure in the chamber is reduced from the atmospheric pressure. At low pressures, such as 1 Torr, the mean free path of the gaseous species in the reaction tube increases, and the condensation process is no longer limited to the space between the substrate and the source material. The effect of the nature of the ambient gas is related mainly to its thermal conductivity. In case of fixed source-substrate spacing, high thermal conductivity of the ambient gas tends to increase the substrate temperature, thus reducing the growth rate. High deposition rate of CdTe films (up to 10 μm/min) is therefore a special feature of the CSS process that benefits the thin film growth in a short span of time.

Deposition pressures between 1 and 30 Torr, substrate temperature from 500 to 600°C, and source temperatures between 700 and 800°C are commonly used for CSS. Sublimation of the compounds produces monatomic Cd and diatomic group VI (Te₂ or S₂) vapor, which recombines by the reverse reaction on the relatively cool substrate. Essentially, the coating process is a chemical vapor deposition with locally generated vapor (sublimation) and a reverse reaction (deposition) evolving no by-products. Due to high vapor pressures of the elements relative to the compounds, depositions of CdTe at temperatures above 500°C result in single phase films with stoichiometry to better than 100 ppm. **Table 1** provides a summary in the range of conditions used for the deposition of the CdTe films.

Substrate temperature	550–620°C
Source temperature	565–625°C
Pressure	1–2 Torr (Ar gas atmosphere)
Spacing	2 mm

Table 1. Deposition conditions used in the CSS growth of CdTe films.

In this study, the substrate temperature is varied in the range of 550–620°C. The source temperature, the total pressure, and spacing are adjusted to result in deposition rates of about 1.0–5.0 μm/min. However, for some films, the pressure during the deposition is kept at 2 Torr. One of the important efforts of this study is to control the film thickness toward stable pinhole free CdTe films of thickness <5 μm. By keeping other deposition parameters constant, the temperature profile is changed according to the desired film thickness. The chamber is

evacuated several times and then is kept at 1.8 Torr of Ar gas to create the appropriate atmosphere for deposition.

2.2. Sintering of source material

Sintering is the procedure of compacting and forming a solid mass of material by heat and/or pressure without melting it to the point of liquefaction. In CSS process, sintering is usually executed to prepare the source material, while fine-powdered CdTe or other materials are used. In cases of chunks, one can skip the sintering process. In sintering, CdTe powder is first put on the empty well on the bottom holder. Then, the powder is heated at specific pressure and temperature to make the powder compact as well as to form solid as shown in **Figure 2**.

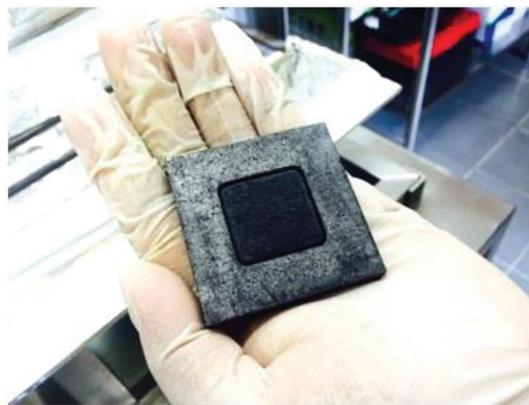


Figure 2. CdTe source material as sintered for CSS process.

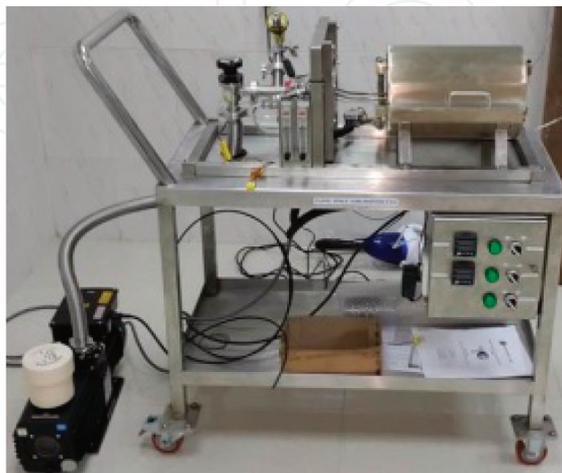
The source material on the graphite box is exhausted for each experiment, so the volume of the material decreases after each sublimation process. CdTe is also deposited on the inside wall of the chamber in regions where the temperature is cooler than the graphite blocks. This means that more than just the amount of CdTe deposited on the sample is released from the source material during each experiment. The parameters used during the sintering are given in **Table 2**.

CSS sintering parameters	Value
Source temperature	700°C
Spacing	1 mm
Pressure	10 Torr (Ar gas atmosphere)
Heating time	30 min

Table 2. CdTe sintering parameters used in CSS.

The chamber has a rotary vacuum pump attached to one flange with the choice to allow gas to flow into the other flange. To control the pumping rate, a valve is positioned between the

pump and deposition chamber, a pipe which bypassed the valve has a smaller diameter to limit the flow of gas. The pressure in the chamber is normally measured by pressure gauges. Argon and nitrogen gases are attached to the system. The argon gas is used as a deposition gas. Nitrogen is generally used for purging and venting the chamber to open the quartz tube (Figure 3).



(a)



(b)

Figure 3. (a) CSS deposition system and (b) CSS grown CdTe thin film on glass.

In general, the CSS chamber is left under vacuum between experiments. When it is needed to open the chamber, gas is fed inside to bring the pressure up to atmosphere. The end flange with the gas inlet can be removed, and the graphite blocks can also be removed from the chamber. The sample is placed in the substrate block, and two glass samples are kept on top working as heat spreaders. The graphite blocks are then placed at the end of the tube, and the thermocouples are positioned within the blocks. The blocks are then pushed into the centre of the quartz tube, and the chamber is pumped to a vacuum. After a vacuum has been reached, the gas pressure gauge could then be adjusted to acquire the desired pressure within the chamber after a few purging of ambient inside. When the environment is stabilized, the heating

sequence starts, and the temperature monitoring begins. The superstrate configuration is basically used to deposit CdTe on top of CdS deposited films. The system is maintained at the set temperatures by means of radiative heating using a total of 2 kW halogen lamps on top and bottom. The thermocouples are inserted into the graphite holders to monitor the growth temperatures (**Figure 4**).

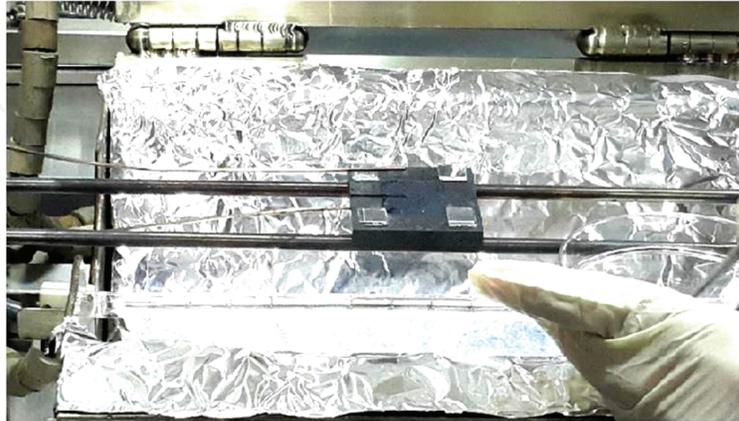


Figure 4. Inside view of the CSS chamber with spacers placed on top of bottom holder.

2.3. Significance of temperature profiles

The substrate temperature of CdTe thin films during the growth is an essential parameter to obtain high-quality films ultimately resulting in high-efficiency CdTe/CdS thin film solar cells. During the fabrication of CdTe/CdS full cell, high temperature is required for CdTe thin films for inter-diffusion of CdS and CdTe to form $\text{CdS}_{1-x}\text{Te}_x$ layer. The formation of a $\text{CdS}_{1-x}\text{Te}_x$ mixed crystal layer modifies the electrical junction into the CdTe improving the electrical and photovoltaic characteristics of the junction [24]. The extent of inter-diffusion depends on the rate of deposition and the substrate temperature [25].

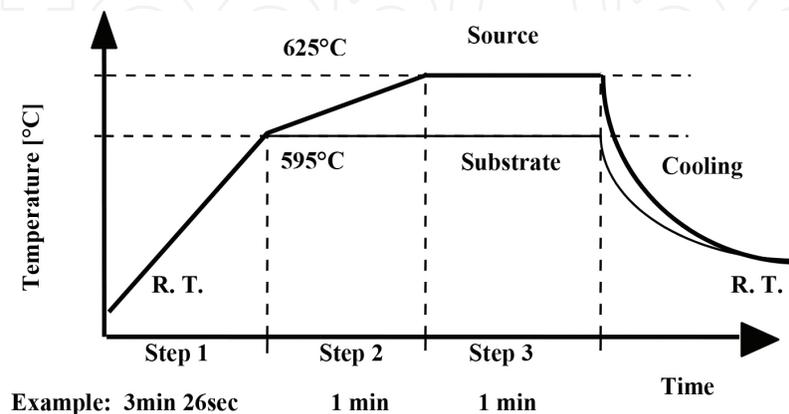


Figure 5. A typical temperature profile for CdTe growth of 5 μm and above.

In many literatures, it is found that the high conversion efficiencies obtained from CSS CdTe films have been attributed to the high substrate temperature. The use of high substrate temperatures is considered to uphold the interface reaction between the CdS and CdTe. Considering all the above facts, the temperature profile (described as heat profile in some literatures) is highlighted strongly. In order to achieve high efficiency, it is more significant to attain high-quality CSS CdTe films. Several temperature profiles have been utilized to differentiate the cell performance. The temperature profile of the growth process is illustrated in **Figure 5**.

2.4. High-efficiency CdTe solar cells (>5 μm) from CSS technique

Although a number of important factors in CSS growth, which are supposed to bear significant roles in overall performance, are demonstrated earlier, the most important issue is to grow high-quality CdTe film regardless of its growth technique. To study as well as to make an effort in achieving such high-quality CdTe films, several temperature profiles were adopted during the growth by CSS here. All these temperature profiles were evaluated from their related results such as solar cell characteristics. In general, it has been noticed that the temperature profiles have important effect on the crystallinity as well as the thickness of the CdTe layer (**Figure 6**).

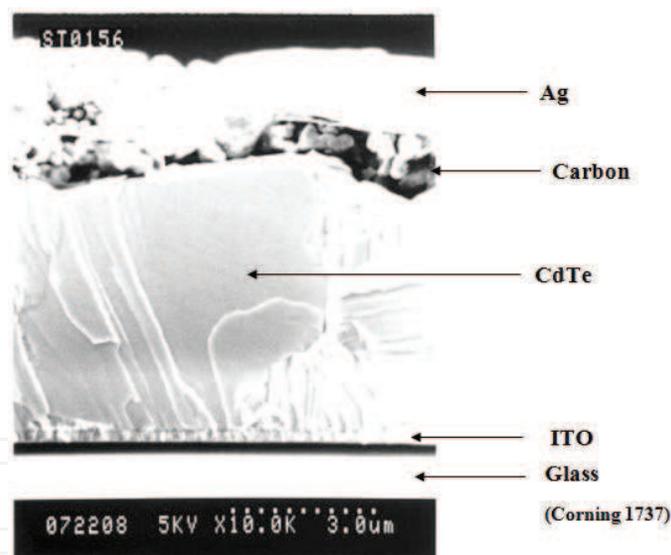


Figure 6. FESEM cross-sectional view of CdTe solar cell grown by CSS.

The most common temperature profile, which is recommended by the leading comrades in this field of CdTe solar cell fabrication, consisted of three steps with all high temperatures is shown in **Figure 5**. After the initial ramp-up step, the second step is supposed to have a great role in the crystallization of CdTe. The third step is important for stabilizing the microcrystals and the gaining the growth of CdTe layer. A part of the study also found unintentional growth of CdTe during the rise of temperature at the first step of the temperature profile. Even at low temperatures, small seed grains of CdTe were observed. Therefore, investigations have been

carried out for all possible temperature profiles in high temperature region and finally proposed the optimum one, as shown earlier in **Figure 5**, for better quality CdTe films (5–7 μm thick). The key point of this temperature profiles lies in the reverse mode during temperature rise as substrate temperature gets higher than the source temperature at any time dimension until the set temperature. Once the substrate temperature reaches its set point (e.g., 595°C), the source temperature increases until its set point (e.g., 625°C) and then both of them keep the set temperature constant, thus create a temperature difference of 30°C viable for CdTe growth in this case. This type of reverse mode in temperature rise could control the unintentional growth of CdTe at lower temperatures, which (CdTe) is suspected to be lower in quality with pinholes etc. In the modified temperature profile, the unexpected CdTe growth was suppressed to as low as 0.15 μm when the temperature rise of both source and substrate was stopped at the set point of substrate temperature. These CdTe films are then used to make full solar cell devices with the configuration of glass/ITO/CdS/CdTe/C:Cu/Ag. The conversion efficiency of 15.31% with open-circuit voltage (V_{oc}) of 0.811 V, short-circuit current (J_{sc}) of 26.3 mA/cm^2 , fill factor (F.F.) of 0.718 was achieved for the best cell as the highest to date found in the current configuration and process. The thickness of CdTe layer was about 7 μm , and the effective area of the cell was 1 cm^2 . The current-voltage (J-V) characteristics are shown in **Figure 7**.

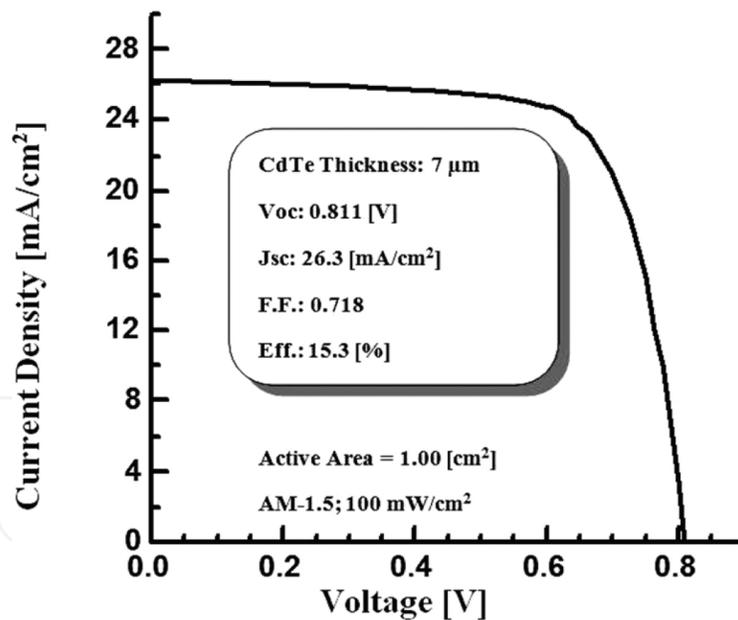


Figure 7. J-V characteristics of the CdTe thin film solar cell.

2.5. Thickness reduction in CdTe by low-temperature growth

The key concern is to obtain high-quality CdTe films regardless of the growth technique. Typically, the temperature corresponds to the source temperature of 625°C and substrate temperature of 595°C for high-efficiency cells, where 5- μm -thick CdTe is grown in this profile.

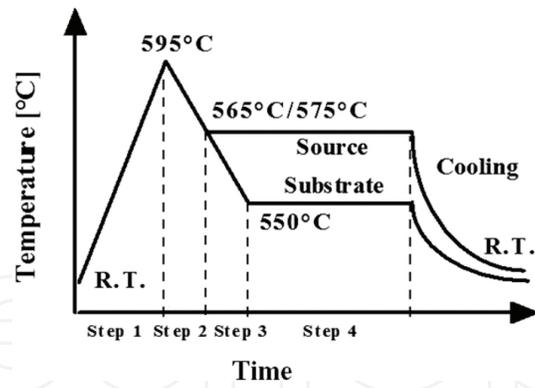


Figure 8. Temperature profile for low-temperature growth of CdTe.

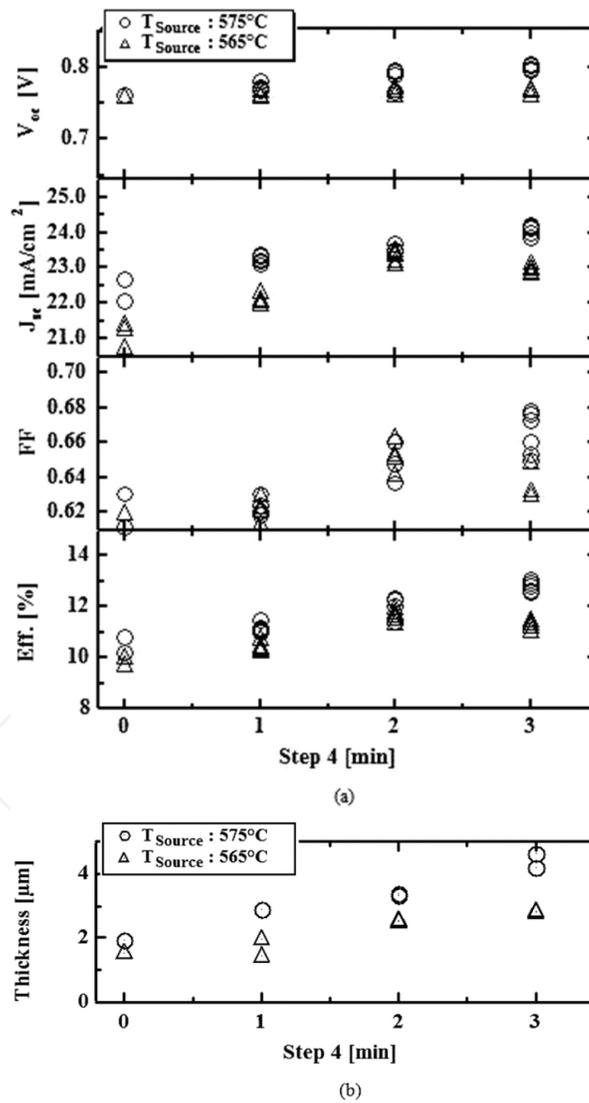


Figure 9. Effect of growth time on the (a) solar cell performance and (b) thickness of CdTe films, grown at low temperature.

Therefore, the temperature reduction in both the source and the substrate was carried out with the aim of obtaining a high-quality, as well as thinner, CdTe layer. No CdTe growth was observed until the source temperature of 530°C and substrate temperature of 500°C were maintained. In the profile shown in **Figure 8**, both the source and the substrate were first heated to a high temperature of 595°C for surface cleaning and then lowered to 575 or 565°C in the case of the source and 550°C in the case of the substrate. Controlling the time in step 4, thickness control (reduction) of the CdTe layer to 1.5 and 2 μm was achieved for source temperatures of 565 and 575°C, respectively.

Figure 9 illustrates the effect of growth time in step 4 on the thickness of the CdTe layer, as well as on the overall performance of solar cells. Thickness could be controlled down to 1.5 μm with a conversion efficiency of 10.4% (V_{oc} : 0.76 V, J_{sc} : 22 mA/cm², F.F.: 0.62, area: 1 cm²) at a source temperature of 565°C. Meanwhile, if the source temperature is increased to 575°C while keeping the substrate temperature unchanged at 550°C, the growth rate remarkably increases. However, the thickness can be controlled down to 2 μm with this profile, with an efficiency of 10.8% (V_{oc} : 0.76 V, J_{sc} : 22.7 mA/cm², F.F.: 0.63, area: 1 cm²). Therefore, a low-growth temperature demonstrates lower possibility of achieving thin CdTe films (1 μm) with high efficiency.

2.6. Control of CdTe thickness by reducing temperature difference

With the aim of achieving high-quality thin films and considering the results presented in previous section, the temperatures of the source and the substrate were increased to 600 and 595°C, respectively. The temperature profile is shown in **Figure 10**.

Moreover, the temperature difference between the two was set to 5°C to reduce the thickness. Thickness control down to 2 μm was possible with an efficiency of 11% (V_{oc} : 0.77 V, J_{sc} : 23.7 mA/cm², F.F.: 0.60, area: 1 cm²). The overall performance deteriorated with the decrease in thickness but showed an improvement compared to the cells grown at lower temperatures as can be found in **Figure 11**. Regardless of the temperature profiles, all the cell performances were affected with the decrease in CdTe film thickness.

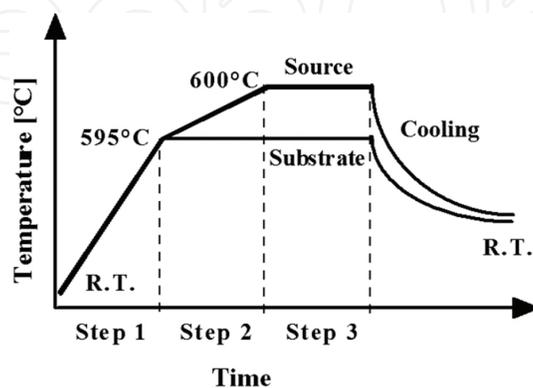


Figure 10. Temperature profile for CdTe growth in CSS with minimal temperature difference between source and substrate.

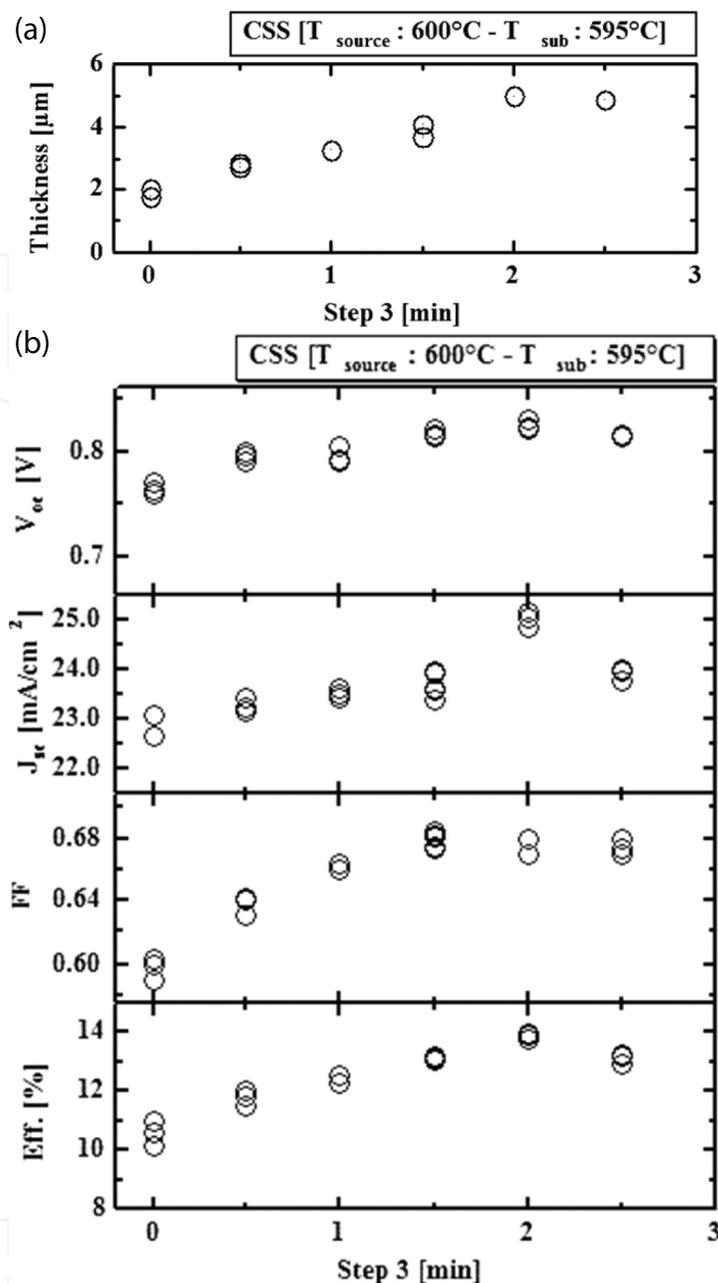


Figure 11. Characteristics of CdTe solar cells (a) and thickness of CdTe films (b), deposited using minimal temperature difference between source and substrate in CSS.

2.7. Growth of 1 μm-CdTe thin films by CSS

As described in earlier sections, several temperature profiles have been used during CSS growth of CdTe to determine the effect of temperature. It has become apparent that temperature plays a significant role in thickness control. Following the temperature profile shown in **Figure 12**, the temperatures of both the substrate and the source were raised together to several peak temperatures, and it was possible to grow thin CdTe layers with thickness from 0.5 to 1.5 μm for peak temperatures from 595 to 620°C.

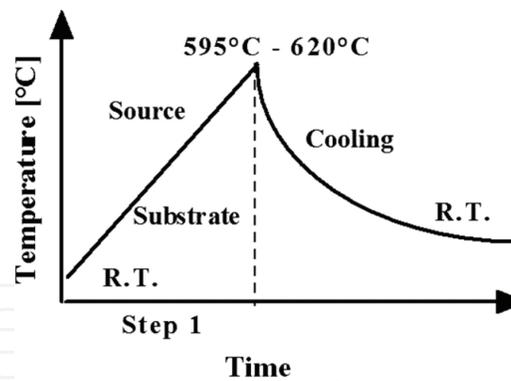


Figure 12. Temperature profile of 1- μm -thick CdTe thin film growth by CSS.

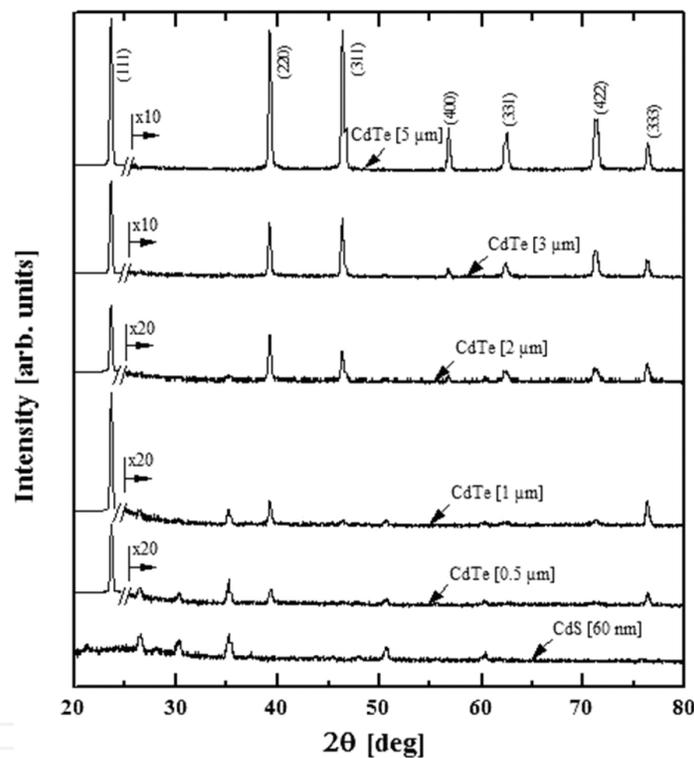


Figure 13. XRD patterns of CdTe films of different thicknesses.

To determine the performances of solar cells with various CdTe layer thicknesses, the I-V characteristics, spectral response, and reflectance were measured, and scanning electron microscope (SEM) and AFM images were taken to evaluate the quality of the films. From the XRD measurement, significant difference among the CdTe films from 5 to 1 μm thick can be observed, as shown in Figure 13. In the case of 1 μm films, some other peaks, probably from ITO or CdS, were found. Compared to thicker films, all the 1- μm -thick films showed strong preferential orientation in the (111) direction. SEM images of the 1- μm -thick CdTe surface shown in Figure 14(a) exhibit the larger grain size of the films. Differently shaped grains have been found in the case of thicker CdTe films.

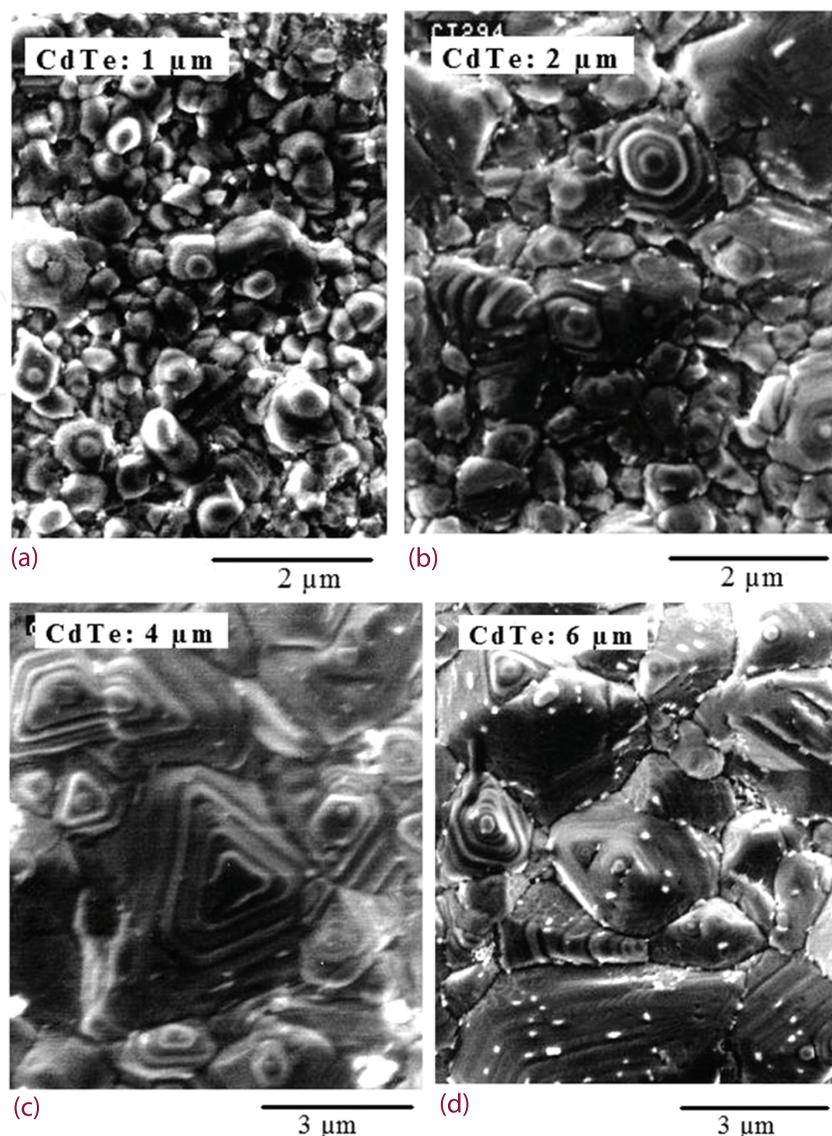


Figure 14. SEM micrographs of the surfaces of (a) 1 μm , (b) 2 μm , (c) 4 μm and (d) 6 μm -thick CdTe films [24].

Films deposited at substrate temperatures of 550–620°C exhibited preferential orientation along the (111) direction as indicated by X-ray diffraction studies. Scanning electron microscope (SEM) images also revealed the high quality of the deposited films of CdTe. The microstructure of CdTe films depends on the substrate temperature, source-substrate temperature gradient, and the crystallinity of the substrate. In general, the grain size increases with the increasing substrate temperature and film thickness.

An efficiency of 8.3% (V_{oc} : 0.73 V, J_{sc} : 20.2 mA/cm², F.F.: 0.57, area: 1 cm²) was achieved for cells with 0.5- μm -thick CdTe, whereas 9.9% (V_{oc} : 0.75 V, J_{sc} : 22 mA/cm², F.F.: 0.6, area: 1 cm²) and 11.4% (V_{oc} : 0.77 V, J_{sc} : 23.7 mA/cm², F.F.: 0.63, area: 1 cm²) were achieved for solar cells with 1- and 1.5- μm -thick CdTe, respectively. The most significant achievement of this effort was the establishment of the growth technique of such thin, high-quality CdTe films, along with reproducibility.

2.8. Overall optimization of CSS grown CdTe solar cells

To be used as a working device, optimization is needed. In order to form an ohmic contact to CdTe thin films, Cu-doped graphite carbon paste was screen-printed, and then, the resulting stacks were subjected to annealing in controlled atmospheres. One related study showed that Cu is distributed as effective acceptors in the CdTe layer, rendering it p-type after annealing. Despite having optimum data for 5- μm -thick CdTe layers, optimization of the annealing temperature was carried out. Significant improvement was found in comparatively low-temperature regions. An excellent improvement in efficiency to 11.2% (V_{oc} : 0.77 V, J_{sc} : 23.1 mA/cm^2 , F.F.: 0.63, area: 1 cm^2) was achieved at the annealing temperature of 345°C. The current-voltage (I-V) characteristic is shown in **Figure 15**. Copper, which is believed to have diffused into the CdTe layer from the carbon layer, functioned as an effective acceptor after annealing at the optimum temperature. Supported by the spectral response data where the cells treated at high temperature exhibit a significant shift near the CdTe absorption edge suggests a possible inter-diffusion of CdS into the CdTe and causes the bandgap of this material to decrease slightly. Since the junction is exposed to such high temperatures, excessive inter-diffusion (which forms $\text{CdS}_x\text{Te}_{1-x}$) is believed to occur, which leads to almost complete consumption of the 1- μm -thick CdTe layer grown during CSS. Therefore, it can be concluded that the uncontrolled formation of such $\text{CdS}_x\text{Te}_{1-x}$ alloy in 1- μm -thick CdTe solar cells can adversely affect the cell performance, which is not possible to overcome by merely treating the stack of layers in any optimum conditions. Therefore, growth during CSS has to be carefully controlled by temperature profiles to achieve high-quality films in terms of grain size, defects, uniformity or homogeneity.

2.9. Conclusion

Close-spaced sublimation (CSS) is one of the most cost-efficient, high-throughput semiconductor coating techniques that offers industrial scalability as well. We developed our custom-

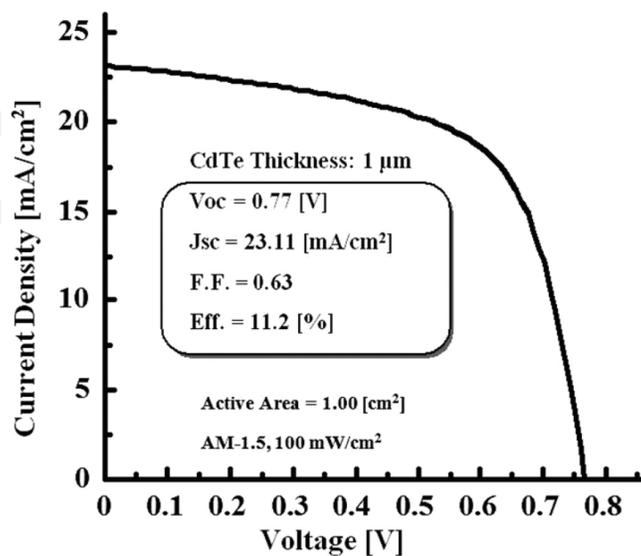


Figure 15. J-V characteristics of 1- μm -thick CdTe solar cell (top record to date) [24].

ized close-spaced sublimation (CSS) apparatus and achieved growth of our material of interest, such as group II-VI compound semiconductor, that is, CdTe for solar cell application. By controlling the temperature profile in steps, thickness of the CdTe film is controlled over 7 to 1 μm without any pinholes in order to realize material conservation as well as to improve the performance through controlling the carrier recombination loss in relatively thicker CdTe absorption layers. The films are investigated by all possible means of thin film characterization like XRD, SEM, UV-Vis, and so on to find its optimized usage in thin film solar cell. The growth of 1- μm -thick CdTe films was achieved by controlling the temperature profile during CSS growth, with reproducibility. Gradual improvements were found in the glass/ITO/CdS/CdTe solar cells as conversion efficiencies of 15.3% for 7- μm -thick, 14.3% for 5- μm -thick, 11.4% for 1.5- μm -thick, and 9.9% for 1- μm -thick CdTe films grown by CSS. Moreover, after a rigorous optimization in post-deposition and back electrode formation annealing profiles, conversion efficiency of 11.2% in the case of 1- μm -thick CdTe was achieved, in air mass 1.5 without antireflection coating as the best value to date. All the results have shown successful deposition of CdTe by this customized close-spaced sublimation (CSS) technique and therefore verify its implication to similar kind of semiconductors for solar cells or other purposes.

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References

- [1] Romeo, N., Bosio, A., Romeo, A. An innovative process suitable to produce high-efficiency CdTe/CdS thin-film modules. *Solar Energy Materials and Solar Cells*. 2010; 94(1): 2–7.
- [2] McCandless, B. E., Dobson, K. D. Processing options for CdTe thin film solar cells. *Solar Energy*. 2004; 77(6): 839–856.

- [3] Ferekides, C. S., Marinskiy, D., Viswanathan, V., Tetali, B., Palekis, V., Selvaraj, P., Morel, D. L. High efficiency CSS CdTe solar cells. *Thin Solid Films*. 2000; 361: 520–526.
- [4] Britt, J., Ferekides, C. Thin film CdS/CdTe solar cell with 15.8% efficiency. *Applied Physics Letters*. 1993; 62: 2851–2852.
- [5] Ferekides C., Britt J., Ma Y., Killian L. High efficiency CdTe solar cells by close spaced sublimation. *Proceedings of 23rd IEEE Photovoltaic Specialists Conference, New York, USA, 1993*, p. 389–393.
- [6] Chu, T. L., Chu, S. S. Recent progress in thin-film cadmium telluride solar cells. *Progress in Photovoltaics: Research and Applications*. 1993; 1(1): 31–42.
- [7] Chu, T. L., Chu, S. S., Britt, J., Chen, G., Ferekides, C., Schultz, N., Wang, C., Wu, C. Q. High efficiency thin film cadmium telluride solar cells. *Photovoltaic Advanced Research and Development Project*. 1992; 268: 88–93.
- [8] Anthony, T. C., Fahrenbruch, A. L., Peters, M. G., Bube, R. H. Electrical properties of CdTe films and junctions. *Journal of Applied Physics*. 1985; 57: 400–410.
- [9] Chu, T. L., Chu, S. S., Ang, S. T. Electrical properties of CdS/CdTe heterojunctions. *Journal of Applied Physics*. 1988; 64(3): 1233–1237.
- [10] Fahrenbruch, A. L., Bube, R. H. *Fundamentals of Solar Cells* (Academic, New York), 1983, p. 231–234.
- [11] Chu, T., Chu, S., Ferekides, C., Britt, J., Wu, C. Thin-film junctions of cadmium telluride by metal organic chemical vapor deposition. *Journal of Applied Physics*. 1992; 71: 3870.
- [12] Albright, S. P., Singh, V. P., Jordan, J. F. Junction characteristics of CdS-CdTe solar cells. *Solar Cells*. 1998; 24: 43–56.
- [13] McCandless, B. E., Moulton, L. V., Birkmire, R. W. Recrystallization and sulfur diffusion in CdCl₂ treated CdTe/CdS thin films. *Progress in Photovoltaics: Research and Applications*. 1997; 5(4): 249–260.
- [14] Ringel, S. A., Smith, A. W., MacDougall, M. H., Rohatgi, A. The effects of CdCl₂ on the electronic properties of molecular-beam epitaxially grown CdTe/CdS heterojunction solar cells. *Journal of Applied Physics*. 1991; 70(2): 881–889.
- [15] Singh, V. P., Brafman, H., McClure, J. C. Characterization of thin film CdS/CdTe solar Cells. *Solar Cells*. 1991; 31: 23–38.
- [16] Massalski, T. B., Okamoto, H., Subramanian, P. R., Kacprzak, L. *Binary Alloy Phase Diagrams* (2nd Edition). ASM International, Materials Park, Ohio, USA, 1990.
- [17] Greenberg, J. H. P-T-X phase equilibrium and vapor pressure scanning of non-stoichiometry in CdTe. *Journal of Crystal Growth*. 1996; 161: 1–11.
- [18] Greenberg, J. H., Guskov, V. N., Lazare, V. B. P-T-X phase diagram cadmium-tellurium. *Materials Research Bulletin*. 1992; 27: 997–1001.

- [19] Guskov, V. N., Izotov, A. D. Thermodynamic principles of the synthesis of CdTe, ZnTe, and CdZnTe solid solutions. *Inorganic Materials*. 2008; 44: 1409–1433.
- [20] De Lary, B., Finch, A., Gardner, P. J. Thermodynamic functions for the congruent sublimation of cadmium telluride. *Journal of Crystal Growth*. 1983; 61: 194–198.
- [21] Alamri, S. N. The growth of CdTe thin film by close space sublimation system. *Physica Status Solidi (A)*. 2003; 200: 352–360.
- [22] Nagayoshi, H., Suzuki, K. Growth of thick CdTe films by close-space-sublimation technique. *IEEE Nuclear Science Symposium Conference Record, Rome, Italy, 2004*, vol. 1–7, p. 4411–4414.
- [23] Anthony, T. C., Fahrenbruch, A. L., Bube, R. H. Growth of CdTe films by close-spaced vapor transport. *Journal of Vacuum Science and Technology A*. 1984; 2: 1296–1302.
- [24] Amin, N., Isaka, T., Okamoto, T., Yamada, A., Konagai, M. Prospects of thickness reduction of the CdTe layer in highly efficient CdTe solar cells towards 1 μm . *Japanese Journal of Applied Physics*. 1999; 38: 4666–4672.
- [25] Wu, X., Coutts, T. J., Mulligan, W. P. Properties of transparent conducting oxides formed from CdO and ZnO alloyed with SnO₂ and In₂O₃. *Journal of Vacuum Science and Technology A*. 1997; 15(3): 1057–1062.

