

A GROWTH MODEL TO PREDICT THE COMPOSITION OF CADMIUM TELLURIDE FILMS

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ABSTRACT: In this study, Bube's growth model for cadmium telluride (CdTe) polycrystalline thin film was re-examined with a view to avoiding their assumptions that neglect the vapor pressures of Cd and Te₂ near the film. We proposed a new thermodynamic growth model based on the fact that there is an experimentally verified characteristic ratio (α) of equilibrium partial pressures $P_{Cd}/2P_{Te2}$ that depends on the temperature T and CdTe stoichiometry. By writing $P_{Cd}(0) = 2\alpha(0)P_{Te2}(0)$ and $P_{Cd}(h) = 2\alpha(h)P_{Te2}(h)$, where $\alpha(0)$ is determined by the source stoichiometry, we can solve the equations for $\alpha(h)$ and thereby determine the stoichiometry of CdTe thin film grown under physical vapor deposition (PVD) condition. Simulation was performed to predict the stoichiometry of CdTe thin film as a function of source stoichiometry for various temperature conditions. The results show that for a typical CdTe PVD process with $T_{source} > T_{thin\ film}$: (1) stable deposition, without non-stoichiometric composition shift, can be achieved at the congruent-growth stoichiometry; (2) any stoichiometric deviation from the congruent sublimation point becomes more substantial (in the same direction) in the thin film than in the source; (3) larger ΔT between source and thin film results in more composition shift.

Keywords: CdTe, photovoltaic, growth model.

1 INTRODUCTION

Cadmium telluride (CdTe) thin film photovoltaic technology has demonstrated its commercial success and great potential in the solar energy industry. CdTe is a group II-VI semiconductor with bipolar intrinsic doping capability [1]. The electrical properties of non-doped CdTe depend sensitively on the compound stoichiometry. Non-stoichiometric CdTe film results in either n- or p-type conductivity [2]. While excess Cd yields n-type conductivity, excess Te produces p-type films.

CdTe thin film solar cells are fabricated as a hetero-junction structure, in which the CdTe layer is usually p-type acting as a photo absorbing layer to generate carriers. In the last 30 years, most CdTe photovoltaics (PV) technologies have been using Te-rich CdTe. Some experts in the field believed that at a given temperature, the higher vapor pressure of Cd than that of Te₂ causes loss of Cd during deposition, and the deposited CdTe can be Te-rich even if the source material is stoichiometric [3,4]. The most commonly used extrinsic doping in Te-rich CdTe is group-I dopants, such as Cu. However, the PV technologies based on the use of Te-rich CdTe combined with Cu as dopants and Cl as passivants have failed to produce hole density greater than 10^{15} cm^{-3} . This contributed to the stagnation of open-circuit voltage (V_{oc}) for 30 years.

The recent breakthrough in monocrystalline CdTe solar cells with V_{oc} breaking 1 V barrier demonstrated a new direction of the technology by shifting to a Cd-rich stoichiometry [5]. Through external doping with group V elements, e.g. P or As, Cd-rich CdTe becomes p-type with hole densities exceeding 10^{17} cm^{-3} . Potentially, PV technologies based on the use of Cd-rich CdTe may play an extremely important role in the future product market of CdTe solar panels.

For both Te-rich and Cd-rich approaches, substantial gains in V_{oc} cannot be possible with intrinsic doping, but

rely on external doping. To effectively introduce external dopants, favorable condition of CdTe stoichiometry is prerequisite. For Te-rich CdTe, the presence of intrinsic defects V_{Cd} enables p-type Cu doping by placing Cu onto the Cd sites to form substitutional Cu_{Cd} [6,7,8]. For Cd-rich CdTe, the presence of intrinsic defects V_{Te} enables p-type P doping by placing P onto the Te sites to form substitutional P_{Te} [6].

Clearly, stoichiometric effects in CdTe is one important factor not only determining the intrinsic electrical properties, but also correlating to the processing technologies that enable the fabrication of high performance thin film PV devices. The CdTe polycrystalline thin films are usually accomplished by physical vapor deposition (PVD). Until recently, the theory and modeling of the PVD process, either close-space sublimation (CSS) or vapor-transport deposition (VTD) of the CdTe polycrystalline thin film however still has some fundamental flaws. The stoichiometric growth condition was incorrectly expressed in several studies, where the stoichiometric condition of CdTe thin film growth was modeled as $P_{Cd} = 2P_{Te2}$ both near the source and near the thin film [9,10]. As the model only considers the reversible dissociation and recombination of $CdTe(s) \leftrightarrow Cd(g) + 1/2 Te_2(g)$, such a fixed pressure ratio of 2 lacks theoretical as well as experimental groundings.

The correct stoichiometric condition of CdTe thin film growth was previously expressed as $J_{Cd} = 2J_{Te2}$ by Bube et al. [11], and by Chin et al. [12], where J_{Cd} and J_{Te2} are the diffusive fluxes of Cd and Te₂, respectively, from the source to the superstrate (substrate) on which CdTe thin film is being deposited. In this study, we re-visit the growth models reported in these two works. After reviewing both models and discussing their drawbacks, we propose an improved thermodynamic model by introducing an equation of $P_{Cd} = 2\alpha P_{Te2}$, where α is a

characteristic ratio between P_{Cd} and $2P_{Te2}$, determined by CdTe stoichiometry and the temperature. Our growth model achieves an appropriate solution to determine the α value near the thin film. This allows us to predict and thus enables us to control the stoichiometry of CdTe thin film as a function of CdTe source stoichiometry. The results of simulation are shown for various source-film temperature combinations.

2 THEORETICAL MODEL OF CDTE THIN FILM GROWTH

A model of CSS CdTe thin film growth was proposed by Bube et al. in 1984 [11]. In their modeling, the stoichiometric condition was correctly expressed as:

$$J_{Cd} = 2J_{Te2}$$

where J_{Cd} and J_{Te2} are the diffusive fluxes of Cd and Te₂, respectively, from the source at $z = 0$ to the superstrate at $z = h$, and h is the spacing between the source and the superstrate on which CdTe thin film is being deposited. In Bube's approach, there were 4 unknowns:

$P_{Cd}(0)$, $P_{Te2}(0)$, $P_{Cd}(h)$ and $P_{Te2}(h)$ but only 3 equations, i.e. the equation of the stoichiometric condition, and the two equations of chemical reaction equilibrium near the source (0) and near the thin film (h):

$$K(0) = P_{Cd}(0)\sqrt{P_{Te2}(0)} = \exp\left[\frac{-\Delta G_{CdTe}(T_0)}{RT_0}\right]$$

$$K(h) = P_{Cd}(h)\sqrt{P_{Te2}(h)} = \exp\left[\frac{-\Delta G_{CdTe}(T_h)}{RT_h}\right]$$

The steady-state diffusive fluxes of Cd and Te₂, under diffusion-limited transport condition, are described by Fick's first law

$$J_{Cd} = \frac{D_{Cd}}{RhT_{avg}} [P_{Cd}(0) - P_{Cd}(h)]$$

$$J_{Te2} = \frac{D_{Te2}}{RhT_{avg}} [P_{Te2}(0) - P_{Te2}(h)]$$

where T_{avg} is the average temperature of source and thin film in unit of K , and D_{Cd} and D_{Te2} are the diffusion coefficients of Cd and Te₂, respectively, in unit of $m^2 s^{-1}$. As carrier gas, such as He or Ar, has usually been used during CSS CdTe deposition, the system can be treated as a binary gas diffusion system of Cd/carrier gas or Te₂/carrier gas. The diffusion coefficients of Cd and Te₂ in the binary system $D_{i,j}$ can be expressed in the Stefan-Maxwell form [13]

$$D_{i,j} = \frac{3kT_{avg}}{8P_{total}\sigma_{ij}^2} \sqrt{\frac{kT_{avg}}{2\pi} \left(\frac{1}{m_i} + \frac{1}{m_j}\right)}$$

where k is the Boltzmann constant in unit of $J K^{-1}$, P_{total} is the total pressure in unit of Pascal, $\sigma_{ij} = (\sigma_i + \sigma_j)/2$ is the average collision diameter in unit of meter, and m is the molecular (atomic) weight in unit of kilogram.

To resolve the difficulty of 4 unknowns with 3 equations, Bube et al. assumed that over the temperature range typically used during CSS CdTe growth, the vapor pressures of Cd and Te₂ near the thin film can be neglected, i.e. $P_{Cd}(0), P_{Te2}(0) \gg P_{Cd}(h), P_{Te2}(h)$, if the temperature difference between the source and the film (ΔT) is 70 °C or larger. This in turn introduced an additional equation of

$$2 = \frac{D_{Cd,j}P_{Cd}(0)}{D_{Te2,j}P_{Te2}(0)}$$

which allowed them to solve the set of equations and thus

yield the CdTe growth rate as a function of growth conditions.

There are two major drawbacks in Bube's work. First, the assumption of $P_{Cd}(0), P_{Te2}(0) \gg P_{Cd}(h), P_{Te2}(h)$ does not hold true, as shown by experimental measurements of Cd and Te₂ partial pressures of Cd_{1+x}Te_{1-x} over a relatively wide temperature range [14]. Second, the work only investigated the effects of deposition condition on growth rate, but not on the stoichiometry of CdTe thin film. Modeling for deposition rate of CdTe have been studied quite extensively, considering both diffusion limited and sublimation limited cases [10]. Considering the advanced technologies nowadays to accurately measure the film thickness both in-situ and ex-situ, it is rather more imperative to model and to predict the CdTe thin film stoichiometry. It is worth noting that a non-stoichiometric composition shift of 0.001 at.% in CdTe may have strong influences on the actual carrier density. Such level of changes in stoichiometry may be beyond the detection limit of any experimental methods.

Recently, our research group has demonstrated a novel and convenient method to resolve the difficulty of 4 unknowns with 3 equations encountered in Bube's work, by treating CdTe with small deviation from the perfect stoichiometry as a solid solution of excess pure Te or Cd solute in congruently grown CdTe solvent [12]. In that growth model, we introduced 1 extra unknown - the excess amount of solute in CdTe thin film $\delta(h)$, but 2 additional equations which are the two polynomial equations of partial pressures based on Henry's law near the source (0) and near the film (h):

$$P_i = H_0(i, T) + \delta(h)H_1(i, T) + \delta(h)^2H_2(i, T)$$

$$P_i = H_0(i, T) + \delta(0)H_1(i, T) + \delta(0)^2H_2(i, T)$$

where i indicates Cd or Te₂, and H 's are the coefficients of polynomial that are functions of temperature. Our model was based on the data of experimentally measured equilibrium partial pressures of Cd and Te₂ in binary Cd-Te system as a function of CdTe source stoichiometry, and the coefficients of polynomial for P_{Cd} or P_{Te2} can be obtained by best fitting of experimental data using the polynomial functions. With the excess amount of solute in CdTe source $\delta(0)$ being given - determined by source stoichiometry, we were able to solve the equations and obtain the corresponding value of $\delta(h)$ for CdTe thin film grown under PVD condition.

Perhaps, the most significant advance in our previous modeling work was that the stoichiometry of CdTe thin film under PVD growth was shown to be determined by the stoichiometry of CdTe source as well as the growth condition. This dependence was preliminarily demonstrated for one source temperature and three different thin film temperatures. Following our previous work, we found it worthwhile to present a dedicated work, which models and predicts the stoichiometry of CdTe thin film as a function of the source stoichiometry, for a wider range of temperatures that will be commonly used for a typical CdTe PVD deposition. The potential results should be highly useful to the field of CdTe PV technologies. The scientists and engineers could use the work as a guidance to fine tune the growth parameters and source stoichiometry, aiming to reach a desired CdTe thin film stoichiometry.

In this study, Bube's growth model for CdTe is re-examined with a view of avoiding his assumptions to solve the equations. Our previous assumption of using Henry's

law - despite its convenience - will be also avoided, because it has not been experimentally proved that the CdTe deviated slightly from the perfect stoichiometric condition can be depicted as the solid solution obeying the Henry's law. To balance the number of equations and the number of unknowns, we herein introduce an equation correlating the equilibrium partial vapor pressures of Cd and Te₂. This equation is based on the fact that there is a characteristic ratio of $P_{Cd}/2P_{Te_2}$ for CdTe, which depends on the temperature T and on CdTe stoichiometry. Considering the source (0) and the thin film (h), respectively, our model provides two additional equations:

$$P_{Cd}(0) = 2\alpha(0)P_{Te_2}(0)$$

$$P_{Cd}(h) = 2\alpha(h)P_{Te_2}(h)$$

but one extra unknown $\alpha(h)$. With $\alpha(0)$ being given by the source stoichiometry, we are able to solve the 5 equations with 5 unknowns, rendering the dependence of $\alpha(h)$ as a function of $\alpha(0)$. It is interesting to note that the dependence of $\alpha(h)$ on $\alpha(0)$ is equivalent to the dependence of $\delta(h)$ on $\delta(0)$.

In our previous model, we used polynomial functions based on Henry's law to fit the experimental data of partial pressures published by Greenberg [14]. However, the fitting and the extrapolation of polynomial coefficients for vapor pressures at lower temperatures lacks a physical grounding as well as the necessary accuracies. In this study, we instead used a numeric method to fit the experimental data of equilibrium partial pressures of Cd and Te₂ as a function of CdTe stoichiometry. The experimental data at temperatures of 1073K, 1123K, 1173K, and 1223K were digitized from the published figures. The digitized graphs were then tabulated in the range of 49.997 to 50.007 at.% Te with an interval of 0.0001 at.%, using the "smooth spline" function provided by Matlab. Such method does not force the data to follow any analytical formula, but rather simply follow any arbitrary data trend. As shown in Fig. 1, the tabulated data satisfactorily match the Greenberg graph. To extrapolate the vapor pressures at lower temperatures for each tabulated stoichiometry, we used the well-known Antoine equation:

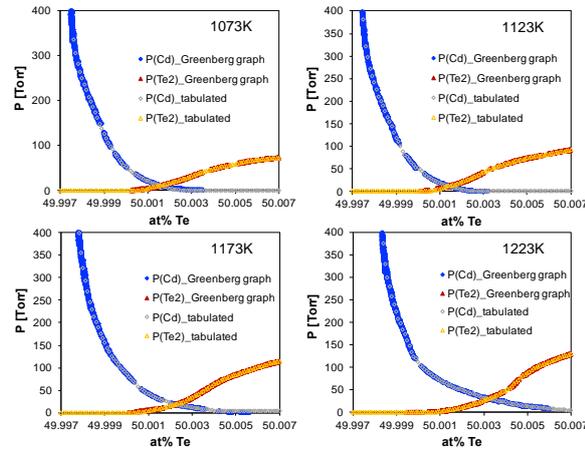


Figure 1: Fitting the experimental data of equilibrium partial pressures of Cd and Te₂ as a function of CdTe stoichiometry using a numeric method. The tabulated data of vapor pressures match the experimental results satisfactorily.

$$\log_{10}P = A - \frac{B}{T}$$

The Antoine equation is a class of semi-empirical correlations describing the relation between vapor pressure and temperature for pure components [15]. Here, we treated each stoichiometry of CdTe as a single component.

3 RESULTS AND DISCUSSION

Fig. 2 summarizes the calculated values of $\alpha(h)$ as a function of $\alpha(0)$ for various CdTe source temperatures in the range of 900 to 1180K. For each source temperature, $\alpha(h)$ values were calculated at five different film temperatures to demonstrate the effect of temperature condition. The source-film temperature combinations were selected to be relevant to a typical CSS or VTD deposition of CdTe thin films. For each CdTe source temperature, the five different film temperatures correspond to $\Delta T (= T_{source} - T_{thin\ film})$ values of 20, 60, 100, 140 and 180K, respectively.

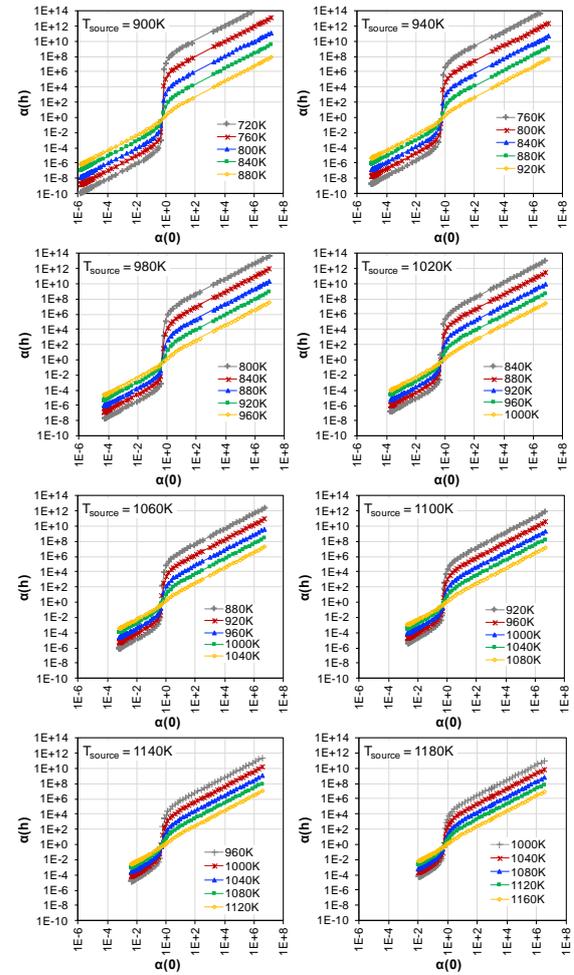


Figure 2: The dependence of $\alpha(h)$ on $\alpha(0)$ for various source temperatures in the range of 900K to 1180K. For each source temperature, $\alpha(h)$ values was calculated at five different film temperatures.

Given the characteristic correlation between the value of α and the stoichiometry of CdTe at a given temperature, the plots of $\alpha(h)$ versus $\alpha(0)$ can be replotted as CdTe film stoichiometry versus CdTe source stoichiometry, with the results being shown in Fig. 3. The characteristic correlations at temperatures of 1073, 1123, 1173 and 1223K were extracted from the experimental data of partial pressures published by Greenberg. The characteristic correlations at other temperatures were obtained by extrapolation of partial pressures using Antoine equation. As shown in Fig. 3, the stoichiometry of CdTe source or thin film was modeled in the range of 49.995 to 50.004 at.% Te for consideration of CdTe thin film PV applications. Further deviation from the perfect CdTe stoichiometry would result in precipitation of elemental Cd or elemental Te phase. The supersaturated solid solution would segregate into a two-phase microstructure with elemental inclusion in the matrix of CdTe compound.

Close inspection of Fig. 2 and Fig. 3 reveals that there is an inflection point in the curve of $\alpha(h)$ vs. $\alpha(0)$ or in the curve of CdTe film stoichiometry vs. source stoichiometry. Near the inflection point, the α ratio of $P_{Cd}/2P_{Te2}$ or the stoichiometry of CdTe shows minimal changes comparing the thin film to the source. This inflection point is positioned on the Te-rich side of stoichiometry in both vapor and solid phases. This observation suggests that the inflection point is near the congruent-growth stoichiometry, rather than near the point of perfect CdTe solid stoichiometry or the point of vapor phase stoichiometric. From the calculated results, stable deposition, without non-stoichiometric composition shift, in principle can be achieved at the congruent-growth stoichiometry. However, as the congruent-sublimation point also shifts with temperature, the CdTe source temperature needs to be controlled in accordance to the source stoichiometry, so that a stable deposition without composition shift can be really achieved.

As shown in Fig. 2 and Fig. 3, on either side of the congruent-growth stoichiometry, any stoichiometric deviation from the congruent sublimation point becomes more substantial (in the same direction) in CdTe thin film than in CdTe source. This modeling result is important for a typical CdTe PVD process with source temperature higher than film temperature. The commonly used CdTe source material with composition close to the perfect CdTe stoichiometry is likely to position on the Te-deficient side of congruent-growth stoichiometry. Consequently, for a typical CdTe PVD process, there is non-negligible shift of CdTe stoichiometry that is however being usually neglected in the field of CdTe thin film PV technologies.

Another point observed from Fig. 2 and Fig. 3 is that larger ΔT between source and thin film during a process of PVD results in more shift in stoichiometry from CdTe source to CdTe thin film. For each source temperature, while the value of ΔT being close to zero, the plot of $\alpha(h)$ vs. $\alpha(0)$ or film stoichiometry vs. source stoichiometry shows a correlation of linear dependency. This linear relation makes sense as the partial vapor pressures of Cd or Te₂ remain similar on either side of source or thin film, leading to minimal changes in CdTe stoichiometry. As the value of ΔT increases, apart from the change in partial vapor pressures, there is also a stronger shift in the characteristic correlation between the value of α and the stoichiometry of CdTe. As a result, any stoichiometric deviation from the inflection point becomes more substantial in CdTe thin film as the temperature difference

ΔT increases.

It should be noted that our calculated results have introduced a new considering point among the effects of growth temperature for CdTe thin film PV applications. In general, the thin film growth temperature at the superstrate (substrate) level was believed to affect the quality of CdTe polycrystalline thin film, including the grain size, the defect density, and the film surface morphology [16]. It has also been reported that CdTe thin films deposited at lower substrate temperature show a high degree of porosity between the columnar grains structure [17]. Considering these points, it was argued that a higher growth temperature is more beneficial for growing polycrystalline film with less defects. On the other hand, a lower growth temperature is sometime beneficial from practical viewpoints. For example, a low-temperature solar module fabrication process is needed to accommodate the low strain point of soda-lime-glass superstrate. As demonstrated by the calculated results of current study, the temperature difference ΔT in principle will also affect the stoichiometry of CdTe thin film grown under PVD condition. Since a non-stoichiometric composition shift in CdTe may have strong influences on the actual carrier density, it is imperative to consider the temperature effect on stoichiometry while controlling the temperature condition of a deposition process. As the temperature effect on stoichiometry was usually neglected, this makes our work new and useful to the field of CdTe PV technologies.

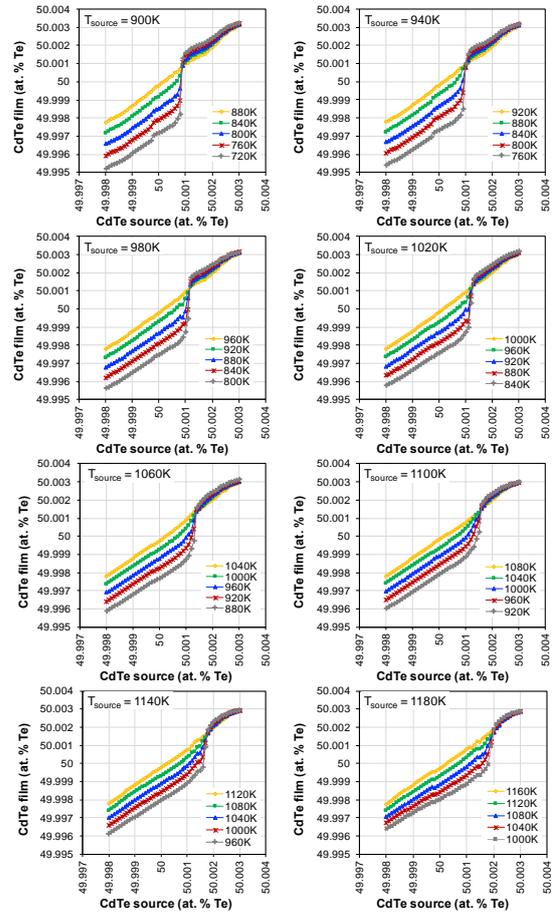


Figure 3: The dependence of CdTe thin film stoichiometry on CdTe source stoichiometry. The results are shown for various source-film temperature combinations.

Derived from the results shown in Fig. 3, we have made a master plot of CdTe composition shift as a function of increasing ΔT , which enables us to predict the stoichiometry of CdTe thin film deposited at a certain source-film temperature combination. As the dependence of composition shift vs. ΔT appears to be linear, the slope and intercept of each line at a given source temperature can be extrapolated using the fitted lines shown in Fig. 4(b) and Fig. 4(c), respectively. Assuming the stoichiometry of CdTe source is known, we can therefore control the stoichiometry of CdTe thin film by fine tuning the temperature condition of a PVD process, using the information provided in Fig. 4.

4 CONCLUSION

The technologies employed for CdTe thin film photovoltaics are strongly dependent on the exact stoichiometry of CdTe thin films. For Te-rich CdTe, Cu-doping is usually used, but there seems to be some fundamental limitations associated. e.g. the doping concentration is limited to less than 10^{15} cm^{-3} due to self-compensation, low carrier lifetime due to Te_{Cd} antisite deep levels, and the stability issue induced by Cu migration. For Cd-rich CdTe, the future seems to be brighter. Experimental study has shown higher V_{OC} for solar cells made from Cd-rich CdTe single crystalline absorber layer. The technologies for Cd-rich material use P- or As-doping, different from that of Te-rich CdTe. Therefore, it is important to foresee the stoichiometry of CdTe films grown under PVD condition, thereby being able to determine the techniques that should be used during the processing steps. As the deviation from the perfect stoichiometry is most likely too small to be accurately measured using experimental methods, a growth model that predicts and controls the CdTe thin film stoichiometry is highly useful.

In this study, we reported an improved thermodynamic model for CdTe thin films grown under PVD conditions. The model considers a characteristic ratio (α) of equilibrium partial pressures $P_{\text{Cd}}/2P_{\text{Te}_2}$ that depends on the temperature T and CdTe stoichiometry. By introducing two equations $P_{\text{Cd}}(0) = 2\alpha(0)P_{\text{Te}_2}(0)$ and $P_{\text{Cd}}(h) = 2\alpha(h)P_{\text{Te}_2}(h)$, where $\alpha(0)$ is determined by the source stoichiometry, we can solve the equations for $\alpha(h)$ and thereby determine the stoichiometry of CdTe thin film. Simulation was performed to predict the stoichiometry of CdTe thin film as a function of source stoichiometry for various source-film temperature combinations. The results show that for a typical CdTe PVD process with $T_{\text{source}} > T_{\text{thin film}}$: (1) Stable deposition, without non-stoichiometric composition shift, can be achieved at the congruent-growth stoichiometry; (2) Any stoichiometric deviation from the congruent sublimation point becomes more substantial (in the same direction) in the thin film than in the source; and (3) Larger ΔT between source and thin film results in more composition shift.

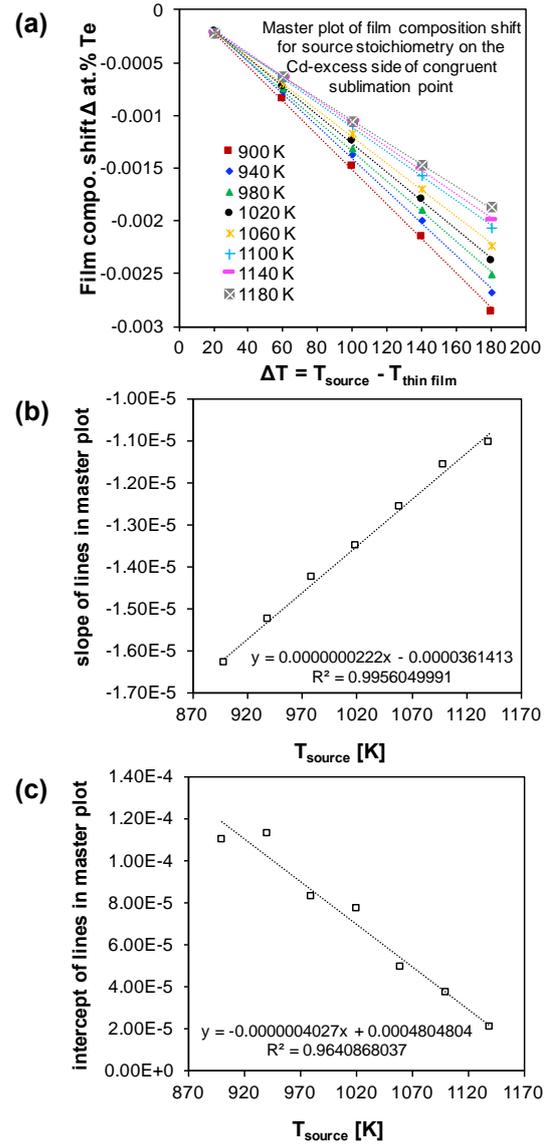


Figure 4: (a) Master plot of CdTe composition shift (% film – % source), on the Cd-excess side of congruent point, as a function of increasing ΔT , for various source temperatures from 900 to 1180K. As the dependence appears to be linear, the slope and intercept of each line (at a given source temperature) shown in master plot can be calculated using the equations shown in (b) and (c), respectively. This allows us to predict the stoichiometry of CdTe thin film deposited at a certain source-film temperature combination.

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6 REFERENCES

- [1] F. Krüger and D. de Nobel, *J. Electron.* **1955**, 1: 190-202.
- [2] H. Y. Ueng, and S. Y. Yang, *J. Renewable Sustainable Energy* 2012, 4: 011605.
- [3] K. Biswas and M. Du, *New Journal of Physics* **2012**, 14: 063020.
- [4] M. Khan, V. Evani, S. Collins, V. Palekis, P. Bane, S. Bakhshi, V. Kendre, S. Vataavu, D. Morel and C. Ferekides, *40th IEEE PVSC Proceedings* **2014**, 2343-2347.
- [5] J. M. Burst, J. N. Duenow, D. S. Albin, E. Colegrove, M. O. Reese, J. A. Aguiar, C.-S. Jiang, M. K. Patel, M. M. Al-Jassim, D. Kuciauskas, S. Swain, T. Ablekim, K. G. Lynn, and W. K. Metzger, *Nat. Energy* **2016** 1: 16015.
- [6] Ji-Hui Yang, Wan-Jian Yin, Ji-Sang Park, Jie Ma, and Su-Huai Wei, *Semicond. Sci. Technol.* **2016**, 31: 083002.
- [7] Jie Ma, Su-Huai Wei, T. A. Gessert, and Ken K. Chin, *Physical Review B* **2011**, 83: 245207.
- [8] Ken K. Chin, T.A. Gessert, and Su-Huai Wei, *35th IEEE PVSC proceeding* **2010**, 001915-001918.
- [9] S. N. Alamri, *Phys. Status Solidi A: Appl. Res.* **2003**, 200: 352.
- [10] J. L. Cruz-Campa, D. Zubia, *Sol. Energy Mater. Sol. Cells* **2009**, 93: 15–18.
- [11] T. C. Anthony, A. L. Fahrenbruch and R. H. Bube, *J. Vac. Sci. Technol. A*, **1984**, 2, 1296-1302.
- [12] K. K. Chin, Z. Cheng, A. E. Delahoy, *J. Cryst. Growth* **2015**, 418: 32-37.
- [13] R. Eslamloueyan, M.H. Khademi, *Chemometrics and Intelligent Laboratory Systems* **2010**, 104: 195–204.
- [14] J. H. Greenberg, *J. Cryst. Growth* **1996**, 161: 1.
- [15] C. Antoine, *Comptes Rendus des Séances de l'Académie des Sciences* **1888**, 107: 681–684, 778–780, 836–837.
- [16] J. D. Major, *Semicond. Sci. Technol.* **2016**, 31: 093001.
- [17] K. Häfner, H. Morgner, O. Zywitzki, T. Modes, C. Metzner, B. Siepchen, B. Späth, M. Grimm, *26th EUPVSEC proceeding* **2011**, 3052-3054.