Electron beam evaporation deposition of cadmium sulphide and cadmium telluride thin films: Solar cell applications*

Fang Li(方 力)[a], Chen Jing(陈 婧)[a], Xu Ling(徐 岭)[a]†, Su Wei-Ning(苏为宁)[b], Yu Yao(于 瑶)[b], Xu Jun(徐 骏)[a], and Ma Zhong-Yuan(马忠元)[a]

[a] *National Laboratory of Solid State Microstructures and Jiangsu Provincial Key Laboratory of Photonic and Electronic Materials Sciences and Technology, School of Electronic Science and Engineering, Nanjing University, Nanjing* 210093, *China*

[b] *National Laboratory of Solid State Microstructures and Department of Physics, Nanjing University, Nanjing* 210093, *China*

(Received 3 November 2012; revised manuscript received 21 March 2013)

Cadmium sulphide (CdS) and cadmium telluride (CdTe) thin films are deposited by electron beam evaporation. Atomic force microscopy (AFM) reveals that the root mean square (RMS) roughness values of the CdS films increase as substrate temperature increases. The optical band gap values of CdS films increase slightly with the increase in the substrate temperature, in a range of 2.42–2.48 eV. The result of Hall effect measurement suggests that the carrier concentration decreases as the substrate temperature increases, making the resistivity of the CdS films increase. CdTe films annealed at 300 °C show that their lowest transmittances are due to their largest packing densities. The electrical characteristics of CdS/CdTe thin film solar cells are investigated in dark conditions and under illumination. Typical rectifying and photovoltaic properties are obtained.

Keywords: cadmium sulphide, cadmium telluride, electron beam evaporation, solar cell

PACS: 88.40.jm **DOI:** 10.1088/1674-1056/22/9/098802

1. Introduction

Cadmium sulphide (CdS) and cadmium telluride (CdTe) thin films have attracted extensive interest due to their potential applications in solar cell devices. CdS is an n-type semiconductor with a wide direct band gap (2.42 eV), generally used as the window layer deposited on p-type CdTe[1–3] or copper indium selenide ($CuInSe_2$)[4] in hetero-junction thin-film solar cells.[5] CdS and CdTe thin-film solar cells are both generally considered to be one of the most promising candidates for the second generation solar cells, due to their diversified low-cost fabrication techniques and high efficiency.[6]

So far, several deposition techniques of CdS or CdTe film have been developed, including physical methods such as sputtering,[7] vacuum evaporation,[8] close-spaced sublimation (CSS),[1,9] spray pyrolysis,[10] chemical bath deposition (CBD),[1,11,12] and electrodeposition.[13,14] Compared with chemical methods, physical methods help to achieve flow production since the absorption layers are generally deposited by sputtering or evaporation,[1,6] and do not discharge wastewater. Physical methods used for the deposition of CdS films are considered to be a promising substitute for the traditional chemical methods.

Electron beam evaporation (EBE) technique has many advantages over other methods, such as low cost, a high degree of control, convenience, and environmental friendliness. However, insufficient attention has been paid to the depositions of CdS and CdTe films by the EBE technique. In this paper, CdS and CdTe films are successfully prepared by using the EBE method. The influences of the deposition parameters on the properties of thin films are investigated and the potentials of the prepared CdS and CdTe films for solar cell applications are explored.

2. Experimental detail

Thin films of CdS were deposited by electron beam evaporation on silicon and glass substrates at different substrate temperatures, in a range of 25–200 °C. CdS and CdTe thin-film solar cells were fabricated by depositing CdS, CdTe, and back contact layers successively on ITO-coated glass substrates. The substrates were first cleaned in alcohol ultrasonically, then rinsed in deionized water, and dried in nitrogen. CdS and CdTe powder of 99.99% purity were used as the source material. The powder was heated by electron beam at pressures of less than 10^{-3} Pa. The deposition rate was maintained at 0.2 nm/s and the thickness was 150 nm for the CdS films, while the deposition rate was 0.4 nm/s for the CdTe films, measured by a quartz crystal monitor.

The surface morphology was studied with an atomic force microscope (Veeco, NS3D). Both the optical transmission and reflection spectra of CdS thin films were obtained using a UV–VIS–NIR spectrophotometer (Shimazu, UV 3600). The current–voltage analysis of CdS/p-Si heterojunction was performed using a digital electrometer (Keithley, 2611A). A halogen lamp was used as the light source and the light intensity

*Project supported by the National Natural Science Foundation of China (Grant Nos. 61036001 and 60976001), the Priority Academic Program Development of Higher Education Institutions of Jiangsu Province, China, and the National Basic Research Program of China (Grant No. 2013CB632101).

†Corresponding author. E-mail: xuling@nju.edu.cn; okxuling@gmail.com

© 2013 Chinese Physical Society and IOP Publishing Ltd

was measured with a solar power meter (Newport, Sol2A).

3. Results and discussion

3.1. AFM analysis of CdS films

Atomic force microscopy (AFM) is used to study the morphologies of CdS thin films. The surfaces of the films are smooth and continuous, which will help to minimize the number of conducting paths between the electrode and absorption layer. The evaluated root mean square (RMS) roughness values of the films are 2.38, 3.08, 5.77, and 11.13 nm for films deposited at different temperatures, as shown in Fig. 1. These results suggest that the surface quality of CdS film declines slightly with the increase in substrate temperature. As the roughness is generally known to depend strongly on the grain size,[7] it is clear that the growth of grains is promoted by increasing the substrate temperature. Still, it is important to note here that surface smoothness is a highly desired parameter for the CdS films in optoelectric applications to reduce the reflection loss due to roughness-induced surface scattering.[15]

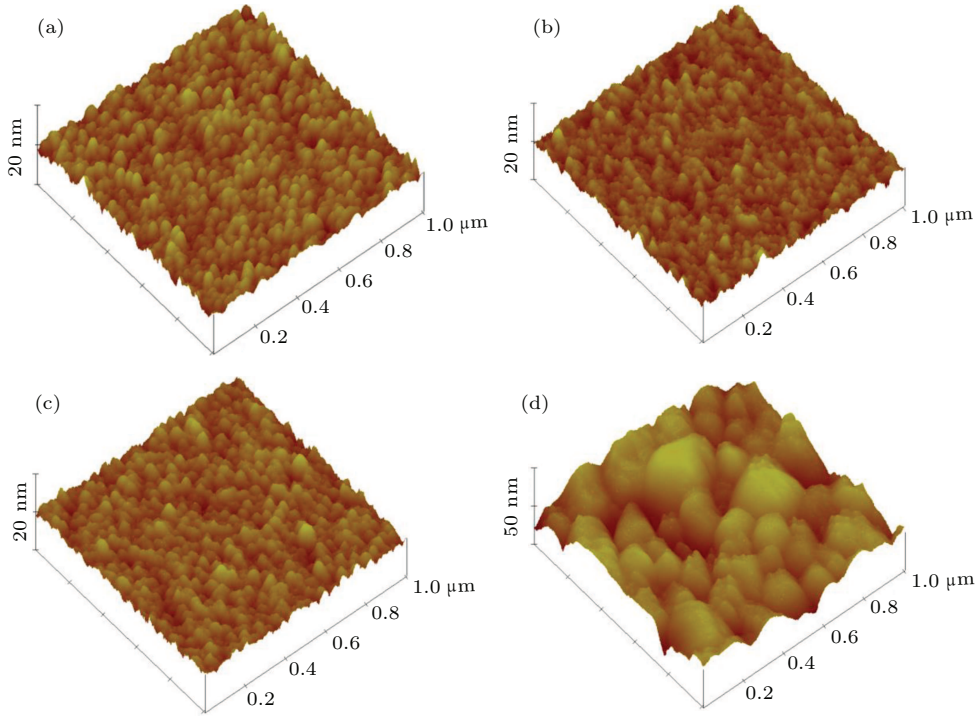


Fig. 1. (color online) AFM images of CdS thin films deposited at different temperatures.

3.2. Hall effect measurement of CdS films

The electrical properties of CdS films also play an important role for the performance of solar cell. The substrate-temperature dependence of the electrical resistivity of CdS film is investigated by the Hall effect measurement. No significant change in carrier mobility is observed. The variations of resistivity and carrier concentration with temperature are shown in Fig. 2.

The resistivity and carrier concentration are found to increase with increasing substrate temperature. As mentioned above, CdS film deposited at a higher temperature is a composition with a lager S/Cd ratio, and the decrease of Cd was reported to reduce the electron density of the film.[16] Thus, the increasing substrate temperature can reduce the Cd/S ratio, leading to the decrease in the carrier concentration and leading the resistivity of the CdS film to rise. As the rise in the resistivity of CdS film would reduce the efficiency of solar cell, many efforts have been made to dope CdS film in order to obtain a CdS film with a low resistivity and a wide band gap.[17]

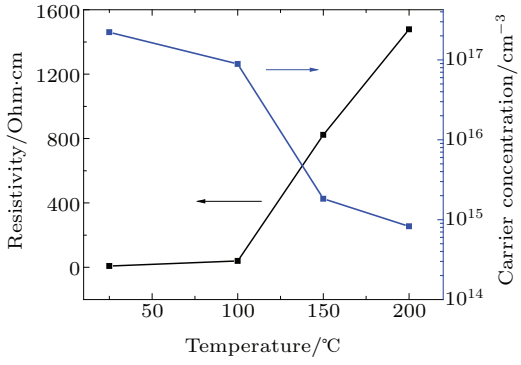


Fig. 2. (color online) Substrate temperature dependences of resistivity and carrier concentration of CdS films.

3.3. Optical analysis of CdS and CdTe film

Comparing the reflection curves of CdS films deposited at different temperatures on silicon substrates in Fig. 3, it can be found that the reflection of CdS film decreases with increasing substrate temperature. This result is in good agreement with the conclusion obtained from AFM analysis. The reflectance

of the film annealed at 200 °C reduces 5% compared with that at 25 °C at wavelengths longer than 700 nm.

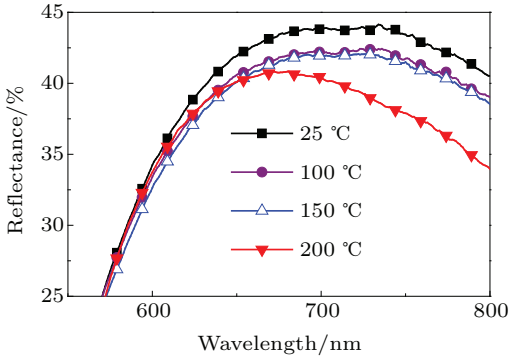


Fig. 3. (color online) Optical reflectance spectra of CdS films deposited at different substrate temperatures.

For a direct transition semiconductor, the optical band gap E_g is calculated using the experimentally determined data of absorption coefficient α from the following equation:[18]

$$(\alpha h\nu)^2 = A(h\nu - E_g), \tag{1}$$

where A is a constant, and $h\nu$ is the energy of incident photon. The energy band gap is estimated from the Tauc plot of $(\alpha h\nu)^2$ versus the photon energy $(h\nu)$, through extrapolating the linear portion of each curve back to the energy axis in Fig. 4. The values of the band gap energy of CdS thin films are found to be in a range of 2.42–2.48 eV and slightly increase with increasing substrate temperature. Such a variation is clearly an advantageous property for CdS film serving as window layer in hetero-junction solar cell since it extends the range of the spectral transmission just into the maximum part of the solar emission spectrum.[19] The sticking coefficient of Cd is reported to decrease as substrate temperature increases, resulting in a change in the stoichiometry of CdS film.[20] Thus, the CdS film deposited at a higher temperature is a composition with a lager S/Cd ratio. It was reported that the rise in the S/Cd ratio leads to an increase in the band gap of CdS film.[21]

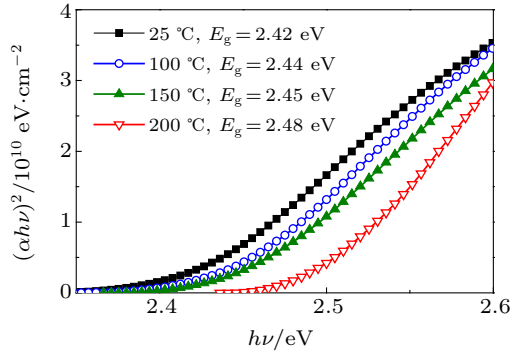


Fig. 4. (color online) Tauc plot of $(\alpha h\nu)^2$ versus $(h\nu)$ for CdS films deposited at different substrate temperatures.

CdTe films with different values of thickness (d) are deposited by the EBE technique and annealed at different temperatures (T_{ann}) in nitrogen. Figure 5 shows the transmittance spectra of CdTe films. Steep absorption edges are observed for all the films, suggesting that film of 700 nm or even more than 700 nm in thickness absorbs nearly 100% of the incident light in the visible region of the solar spectrum. The value of optical band gap is calculated using the Tauc method mentioned above, and found to be around 1.5 eV. Also, it is found that film annealed at 300 °C exhibits the lowest transmittance regardless of film thickness. The packing density of the film increases with increasing annealing temperature, so the increase in the packing density leads to the decrease in transmittance. Owing to the decrease in film thickness by thermal etching at high annealing temperature, the transmittance of the film annealed at 300 °C is lower than that annealed at 400 °C.

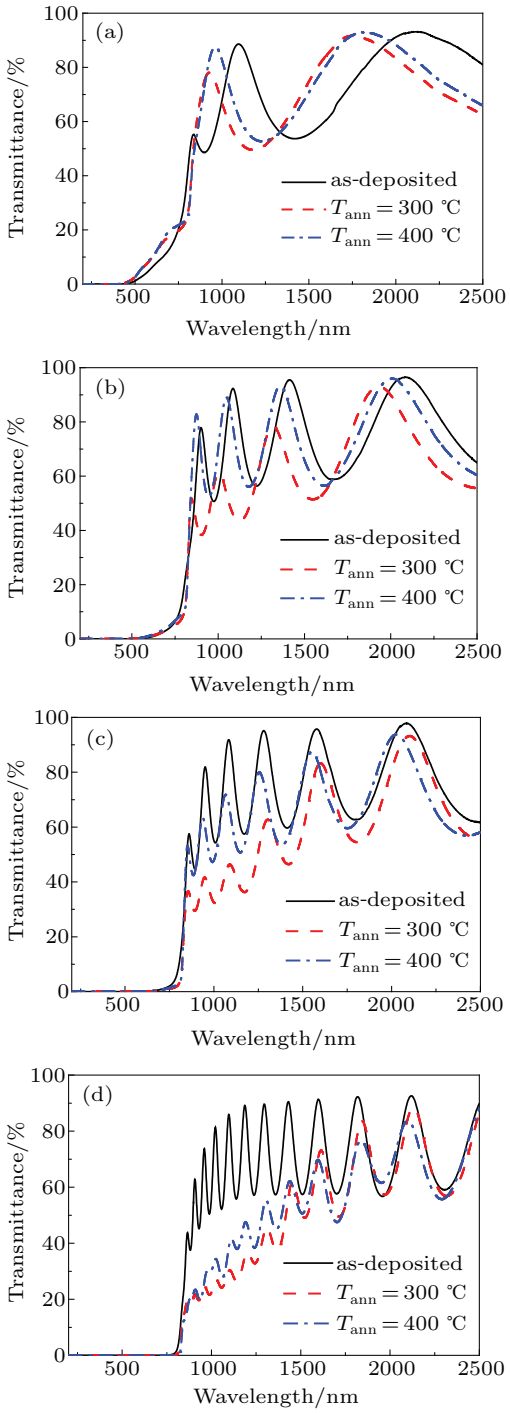


Fig. 5. (color online) Optical transmittance spectra of as-deposited and annealed CdTe films with (a) d = 500, (b) 700, (c) 1000, (d) 2000 nm.

3.4. CdS/CdTe solar cells

To further explore the potentials of the CdS and CdTe films prepared by EBE technique for thin-film solar cell applications, 150-nm CdS film is deposited on ITO-coated glass substrate at 200 °C as a window layer with a large band gap. A 2-μm-thick CdTe film is then evaporated also by the EBE technique. Au is adopted as a bottom electrode. The current–voltage curves shown in Fig. 6 are measured in dark condition and under AM 1.5 global spectrum at room temperature. It is found that the device shows a typical rectifying property and photovoltaic effect. The open-circuit voltage, short-circuit current density, and fill factor of Sample 1 are, respectively, 567 mV, 6.92 mA/cm^2, and 31.61%, leading to an efficiency of 1.24%.

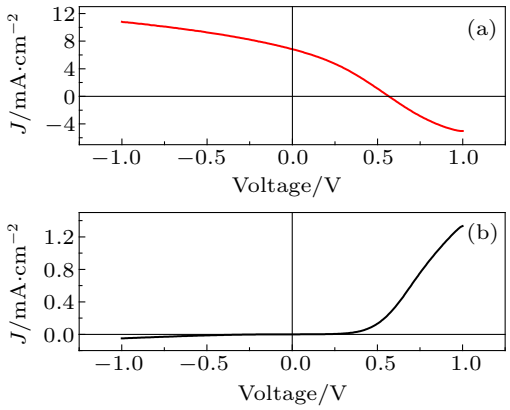


Fig. 6. (color online) The *J*–*V* plots of CdS/CdTe (a) with and (b) without light irradiation.

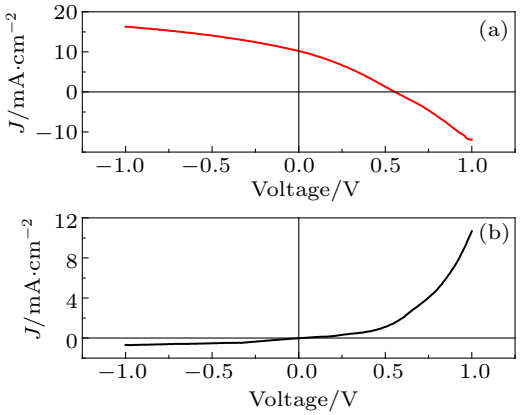


Fig. 7. (color online) The *J*–*V* plots of CdS/CdTe/CuTe (a) with and (b) without light irradiation (bottom).

Because of the high electron affinity of CdTe, a Cu$_x$Te layer of 50 nm in thickness is evaporated before depositing Au electrode, leading to the improvement of the ohmic contact between the active layer and the electrode. Figure 7 show the solar cell characteristics of fabricated CdS/CdTe/CuTe cells in the same condition. The open-circuit voltage of this sample is 567 mV, the same as that of the sample mentioned above. However, the values of short-circuit current density are 10.34 mA/cm^2 and 30.04%, resulting in an efficiency of 1.73%. It is obvious to see the improvement when using a Cu$_x$Te layer to reduce the contact resistance between CdTe film and back electrode.

It is found that both devices show typical rectifying properties and photovoltaic effects. The open-circuit voltage, short-circuit current density, and fill factor of Sample 1 are 567 mV, 6.92 mA/cm^2, and 31.61%, respectively, leading to an efficiency of 1.24%. They are are 567 mV, 10.34 mA/cm^2, and 30.04% for Sample 2, resulting in an efficiency of 1.73%. Obviously, the Cu$_x$Te layer can reduce the contact resistance between p-type CdTe film and back electrode, thus increasing the short-circuit current density and efficiency of the solar cells. In this case, the rate of Te/Cd and the thickness of Cu$_x$Te still need to be optimized to obtain high-efficiency solar cells with a high fill factor.

4. Conclusions

A simple and convenient EBE technique is successfully employed to fabricate CdS and CdTe thin films with a good surface quality, leading to typical optical and electrical properties. The band gap of CdS film is found to increase with increasing substrate temperature. Hall effect measurement shows that the carrier concentration of CdS film declines as substrate temperature increases, causing the rise in resistivity. CdTe film annealed at 300 °C possesses the lowest transmittance. The photovoltaic behavior of CdS/CdTe thin-film solar cell provides further evidence that the EBE technique is attractive to low-cost massive production and large area CdS coatings for solar cell applications.

References

[1] Britt J and Ferekides C 1993 *Appl. Phys. Lett.* **62** 2851
[2] Bayhan H and Ercelebi C C 1997 *Semicond. Sci. Technol.* **12** 600
[3] Ma Y Y, Fahrenbruch A L and Bube R H 1977 *Appl. Phys. Lett.* **30** 423
[4] Shay J L, Wagner S and Kasper H M 1975 *Appl. Phys. Lett.* **27** 89
[5] Li B, Feng L H, Wang Z, Zheng X, Zheng J G, Cai Y P, Zhang J Q, Li W, Wu L L, Lei Z and Zeng G G 2011 *Chin. Phys. B* **20** 037103
[6] Wu X Z 2004 *Solar Energy* **77** 803
[7] Gupta A and Compaan A D 2004 *Appl. Phys. Lett.* **85** 684
[8] Bayhan H and Ercelebi C C 1997 *Semicond. Sci. Technol.* **12** 600
[9] Ferekides C S, Marinskiy D, Viswanathan V, Tetali B, Palekis V, Elvaraj P and Morel D L 2000 *Thin Solid Films* **361** 520
[10] Ma Y Y, Fahrenbruch A L and Bube R H 1977 *Appl. Phys. Lett.* **30** 423
[11] Moualkia H, Hariech S and Aida M S 2009 *Thin Solid Films* **518** 1259
[12] Mendoza-Pérez R, Aguilar-Hernández J, Sastre-Hernández J, Ximello-Quiebrasa N, Contreras-Puentea G, Santana-Rodríguezc G, Vigil-Galána O, Moreno-Garcíaa E and Morales-Acevedod A 2006 *Solar Energy* **80** 682
[13] Sasikala G, Dhanasekaran R and Subramanian C 1997 *Thin Solid Films* **302** 71
[14] Ou S S and Stafsudd O M 1984 *J. Appl. Phys.* **55** 3769
[15] Tigau N, Ciupina V and Prodan G *J. Optoelectron. Adv. Mater.* **20** 06837
[16] Razykov T M, Contreras-Puenteb G, Chornokurc G C, Dybjecc M, Emirovc Yu, Ergasheva B, Ferekidesc C S, Hubbimova A, Ikramova B, Kouchkarova K M, Mathewd X, Morelc D, Ostapenkoc S, Sanchez-Mezab E, Stefanakosc E, Upadhyayae H M, Vigil-Galanb O and Vorobiev Yu V 2009 *Solar Energy* **83** 90
[17] George P J, Sánchez A, Nair P K and Nair M T S 1995 *Appl. Phys. Lett.* **66** 3624
[18] Tauc J 1975 *Amorphous and Liquid Semiconductors* (New York: Plenum Press) p. 212
[19] Jäger H and Seipp E 1981 *J. Appl. Phys.* **52** 425
[20] Wilson J I B and Woods J 1973 *J. Phys. Chem. Solids* **34** 171
[21] Swanepoel R 1983 *J. Phys. E: Sci. Instrum.* **16** 1214