Electronic properties and deep level transient spectroscopy of CdS/CdTe thin film solar cells*

Li Bing(黎 兵), Feng Liang-Huan(冯良桓), Wang Zhao(王 钊), Zheng Xu(郑 旭), Zheng Jia-Gui(郑家贵), Cai Ya-Ping(蔡亚平), Zhang Jing-Quan(张静全), Li Wei(李 卫), Wu Li-Li(武莉莉), Lei Zhi(雷 智), and Zeng Guang-Gen(曾广根)

College of Materials Science and Engineering, Sichuan University, Chengdu 610064, *China*

(Received 30 August 2010; revised manuscript received 20 October 2010)

It is well known that preparing temperatures and defects are highly related to deep-level impurities. In our studies, the CdTe polycrystalline films have been prepared at various temperatures by close spaced sublimation (CSS). The different preparing temperature effects on CdS/CdTe solar cells and deep-level impurities have been investigated by I–V and C–V measurements and deep level transient spectroscopy (DLTS). By comparison, less dark saturated current density, higher carrier concentration, and better photovoltaic performance are demonstrated in a 580°C sample. Also there is less deep-level impurity recombination, because the lower hole trap concentration is present in this sample. In addition, three deep levels, $E_{\rm v} + 0.341$ eV($H4$), $E_{\rm v} + 0.226$ eV($H5$) and $E_{\rm C} - 0.147$ eV($E3$), are found in the 580°C sample, and the possible source of deep levels is analysed and discussed.

Keywords: CdTe, electrical properties, deep level transient spectroscopy

PACS: 71.55.–i, 72.80.Ey, 73.61.–r **DOI:** 10.1088/1674-1056/20/3/037103

1. Introduction

The studies of CdTe thin-film solar cells are the highlights in the photovoltaic industry.[1,2] The main focus of CdTe thin-film solar cells is efficiency elevation. In 1972, Bonnet and Rabenhorst [3] reported that the efficiency of CdS/CdTe thin-film solar cells had achieved 6%. Later, it reached 15.8% in 1993,[4] 16% in 1998[5] and 16.5%[6] in 2001. In the same time 13.38% was reached by our research group. A good many factors restrict the improvement on the efficiency of CdTe thin-film solar cell,[7−9] such as the fabrication technology and the quality of films. Because of uneven film thickness and difficulties in controllable doping CdTe layer, the recombination can take place on CdS/CdTe junction interface and CdTe layer, which probably turns into deep levels. Deep levels could decrease efficiency by capturing photo-induced carriers, and mess band structure.[10,11] Based on previous research,[12] we study the behaviours of deep levels and their effect on device performance in order to understand the change in device performance, which would guide technological improvement, and enhance the efficiency and the stabilization of CdTe thin-film solar cells.

2. Experimental details

The samples were prepared in our laboratory. CdS thin films were deposited on the SnO_2:F/glass by chemical bath deposition (CBD),[13] CdTe thin films were deposited by close space sublimation (CSS), and $CdCl_2$ was sprayed by ultrasonic spraying. Then, the samples were annealed at 400°C in air atmosphere for one hour. The back-contact layer was of Cu_2Te. The samples were compartmentalized into single cells each with an area of 0.125 cm^2, and the electrode of cells was of Au. The characteristic curves of dark I–V and C–V were measured by the 4284 semiconductor testing instrument (Agilent, USA). Deep level transient spectroscopy was obtained by the DLS-83D system (SemiLab, Hungary).

3. Results and discussion

3.1. Measurements of film thickness and solar cell performance

The parameters of light I–V measurements were studied. It is obviously observed that the thickness of film increases with preparing temperature. The temperature has a less influence on open circuit voltage,

*Project supported by the National Natural Science Foundation of China (Grant No. 60506004), and the National High Technology Research and Development Program of China (Grant No. 2003AA513010).

© 2011 Chinese Physical Society and IOP Publishing Ltd

but a strong influence on short circuit current and fill factor.

3.2. Electronic properties

The dark I–V curves at different temperatures are shown in Fig. 1, and the C–V measurement is shown in Fig. 2.

A comparison shows that the sample deposited at 580°C has well back-contact and no reverse back junctions. Especially, the restriction on the characteristic of this sample is better than those of the other samples. According to the dark I–V and the C–V curves, dark saturated current density J_0, diode factor r, carrier concentration $N_{\rm B}$ were calculated. As a conclusion, the sample deposited at 580°C has a maximal carrier concentration, a minimum dark saturation current density, and a best photoelectric performance.

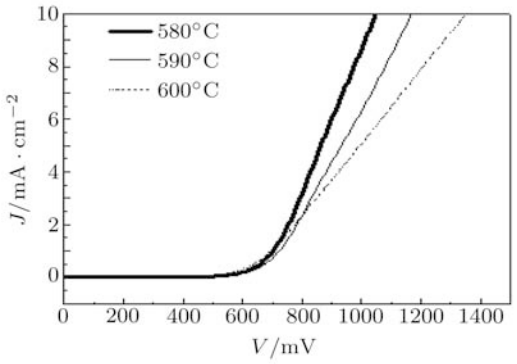


Fig. 1. Dark I–V curves of samples.

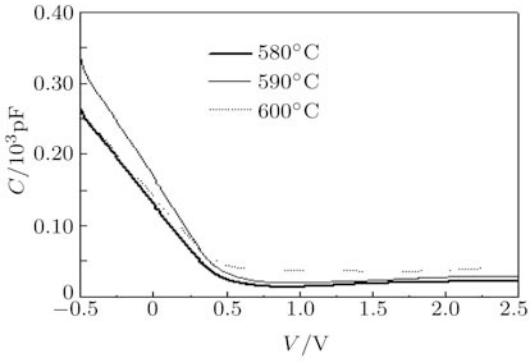


Fig. 2. Dark C–V curves of samples.

3.3. Measurements of DLTS

3.3.1. DLTS of samples prepared at different temperatures

The temperature scanning spectra of samples deposited at different temperatures are shown in Fig. 3.

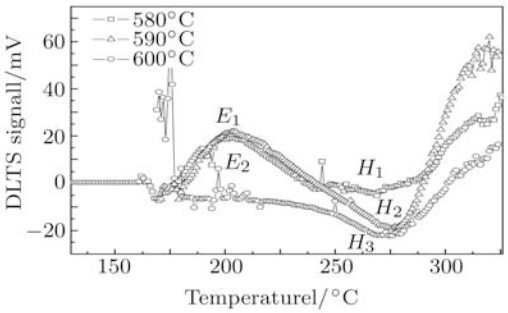


Fig. 3. Temperature scanning spectra of samples by DLTS.

Samples were analysed at a reverse bias of −0.4 V, with a pulse amplitude of 0.6 V, pulse width of 16 μs and pulse frequency of 2500 Hz. Several trap levels were found in a temperature range of 130–320 K. The location and the concentration of deep levels are listed in Table 1.

Table 1. Data of DLTS for samples at different temperatures.

	$E_{\rm T}$/eV	$N_{\rm T}$/cm^{-3}
H_1	$E_{\rm V}+0.328$	1.08×10^{12}
E_1	$E_{\rm C}-0.271$	9.8×10^{11}
H_2	$E_{\rm V}+0.358$	1.17×10^{12}
E_2	$E_{\rm C}-0.255$	1.19×10^{12}
H_3	$E_{\rm V}+0.491$	1.47×10^{12}

The DLTS profiles at different temperatures are shown in Fig. 3. It is evident that the peaks of spectra (H_1, H_2, E_1, E_2, H_3) are attributed to deep levels at three preparation temperatures. Deep levels H_1 and E_1 are observed in the sample deposited at 580°C, H_2 and E_2 are observed in the sample deposited at 590°C, and H_3 is observed in the 600°C sample. The results on analysis and calculation of deep levels show that the deep levels H_1, H_2 and H_3 are in the same hole trap centre near 275 K, while levels E_1 and E_2 are in the same electron trap centre. The carriers surfer the weak combination effect because of lowest deep centre concentration in the sample deposited at 580°C. It indicates that the 580°C sample has a higher carrier concentration, which is consistent with the results in Figs. 1 and 2.

3.3.2. DLTS measurement and analysis of 580° sample

The isothermal deep level transient spectroscopy (IDLTS) was tested on the sample deposited at 580°C with Cu_2Te back contact layer. The IDLTS were performed at temperatures of 199 K, 207 K and 215 K,

with a reverse bias of −2.4 V, positive pulse bias of −0.3 V to make sure no free electrons exist in the depletion region on cells. The width of plus bias is 20 μs for electron relaxation. The range of scanning frequency was 1.066 Hz–2500 Hz. The IDLTS were performed at temperatures of 199 K, 207 K and 215 K, with a reverse bias of −1.8 V, positive pulse bias of −0.3 V and pulse width of 20 μs. Three curves for the cases of 500 Hz, 1500 Hz and 2500 Hz were obtained by heating mode with a rate of 0.2 K/s. The range of scanning temperature was 80 K-320 K. Due to the unstable output signal obtained at low temperature, the temperature range was set in 140 K–320 K.

The curves measured at high frequency are smoother than those at low frequency, especially at low temperature, and the curves present the high signal intensities at high frequency. The curve of 2500 Hz shows that hole traps H_4 and H_5 are near 220 K and 280 K, respectively. E_3 is the trap level near 175 K, which is an electron deep centre. H_4 and H_5 could be identified from the curve for the case of 1500 Hz, while H_4 could be identified from the curve for the case of 500 Hz. Because of the depths of H_4, H_5, E_3 were decreased gradually, the transient response of superficial deep trap levels (0.1–0.3 eV) was weak at low temperature. The signal responses of deep trap levels are imperfect with lots of noises. The properties of CdTe film determine the deep level doping because DLTS signals come from the side of p-type CdTe. The effects of preparing temperature and its uniformity on the property of CdTe film should be investigated furthermore. The Arrhenius plots of sample deposited at 580°C (with Cu_2Te back contact) are shown in Fig. 4.

Through the analysis of our data and their comparison with the data from other literature, H_4 may be considered as $(V_{Cd}{}^{2-}–Cu_i^{+})^{-}$, $(2Cu_{Cd}{}^{-}–V_{Te}{}^{+})$ or the complex related to $V_{Cd}{}^{2-}$, $V_{Te}{}^{+}$.[14,15] The deep level at $E_V + 0.226$ eV is close to Lourenco's investigation,[16] though its source is not determined. H_5 is determined with deep levels of E_V+(0.1–0.2 eV), which is attributed to a complex combined with halogen atoms and other impurities, or related to ionizable cadmium vacancy. An electron trap level at $E_C - 0.140$ eV was discovered by Komin during the study of solar cells without back contact layer, and E_3 (E_C–0.147 eV) is supposed to be from the same source. It possibly was $(V_{Cd}{}^{2-}–Cl_{Te}{}^{+})$ in DX_2 state. Deep level impurities were introduced in process links, such as depositing CdTe films; dealing with $CdCl_2$; annealing and etching treatment, preparation of back contact layer. The study of doping will be carried out by DLTS in future.

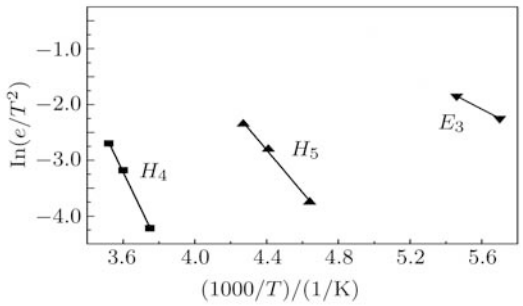


Fig. 4. Arrhenius plots curve of sample deposited at 580°C (with Cu_2Te back contact).

4. Conclusions

CdTe polycrystalline films are deposited at different temperatures. The difference in temperature gives rise to effect on I_{sc} and FF, but no effect on V_{oc}. On the basis of measurements of dark I–V and C–V, the sample deposited at 580°C has a maximal carrier concentration, aminimum dark saturation current density and a best photoelectric performance. According to the SRH theory and the measurements of DLTS, the doping conditions of samples are almost the same. Not only under the temperature scan model, but also under the frequency scan model, were the deep-level impurities consistent at each scanning spot. But the 580°C sample has the weaker recombination of deep-level impurities because of lower trap concentration. Higher concentration of carriers is demonstrated. This is in line with previous I–V and C–V measurements. Based on the frequency scanning spectra and temperature scanning deep level transient spectra, the Arrhenius curve of 580°C sample (with Cu_2Te back contact) is obtained. The deep level location, the concentration of deep level impurity and the capture cross section are calculated. The sources of the three deep-level impurities are analysed and discussed as a basis for further study.

References

[1] Chopra K L, Paulson P D and Dutta V 2004 *Res. Appl.* **12** 69

[2] Morales A and Arturo 2006 *Solar Energy* **80** 675

[3] Bonnet D and Rabenhorst H 1972 *Proc. the 9th Photovoltaic Specialist Conference* p129

[4] Britt J and Ferekides C 1993 *Appl. Phys. Lett.* **62** 2851

[5] Aramoto T, Kumazama S, Higuchi H, Arita T, Shibutani S, Nishio T, Nakajima J and Murozono M 1997 *Jpn. J. Appl. Phys* **36** 6304

[6] Wu X, Keane J C, Dhere R G, DeHart C, Albin D S, Duda A, Gessert T A, Asher S, Levi D H and Scheldon P 2001 *Proceedings 17th European Photovoltaic Solar Energy Conference* p995

[7] Murali K R and Jayasutha B 2007 *Materials Science in Semiconductor Processing* **10** 36

[8] Morgan D, Tang J, Kaydanov V, Ohno T R and Trefny J U 1999 *AIP Conf. Proc.* **462** 200

[9] Bube R H 1998 *Photovoltaic Materials*(London: Imperial College Press)

[10] Jaros M 1982 *Deep Levels in Semiconductors* (Bristol: Adam Hilger Ltd)

[11] Lang D V 1974 *J. Appl. Phys.* **45** 3023

[12] Wang Z, Li B, Zheng X, Xie J, Huang Z, Liu C, Feng L H and Zheng J G 2010 *Chin. Phys.* B **19** 027303

[13] Moualkia H, Hariech S, Aida M S, Attaf N and Laifa E L 2009 *Journal of Physics D-Applied Physics* **42** 135404

[14] Komin V, Tetali B and Viswanathan V 2003 *Thin Solid Films* **431** 143

[15] Castaldini A, Cavallini A and Fraboni B 1998 *J. Appl. Phys.* **83** 2121

[16] Lourenco M A, Yip Kum Yew and Homewood K P 1997 *J. Appl. Phys.* **82** 1423