

# Deep level transient spectroscopy investigation of deep levels in CdS/CdTe thin film solar cells with Te:Cu back contact\*

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Deep levels in CdS/CdTe thin film solar cells have a potent influence on the electrical property of these devices. As an essential layer in the solar cell device structure, back contact is believed to induce some deep defects in the CdTe thin film. With the help of deep level transient spectroscopy (DLTS), we study the deep levels in CdS/CdTe thin film solar cells with Te:Cu back contact. One hole trap and one electron trap are observed. The hole trap H1, localized at  $E_v + 0.128$  eV, originates from the vacancy of Cd ( $V_{Cd}$ ). The electron trap E1, found at  $E_c - 0.178$  eV, is considered to be correlated with the interstitial  $Cu_i^+$  in CdTe.

**Keywords:** deep level transient spectroscopy, CdS/CdTe solar cells, Te:Cu back contact

**PACC:** 7340L, 7360L

## 1. Introduction

CdS/CdTe thin-film solar cell is regarded as one of the leaders of low-cost, large-scale photovoltaic applications. With a band gap energy of 1.5 eV at room temperature, CdTe thin film is suitable for the actinic absorption at the AM1.5 solar spectrum. The theoretical maximum efficiency for these cells is close to 30%,<sup>[1]</sup> but the best result for polycrystalline CdS/CdTe solar cells is about 16%.<sup>[2]</sup> For obtaining low-resistance contact to CdTe and higher efficiency, back contact is a fateful step in the fabrication process of polycrystalline CdS/CdTe solar cells. Because of the developed understanding of the properties of this device region, various high quality back contacts are being used currently, for instance ZnTe/ZnTe:Cu, HgTe:Cu, Te:Cu.<sup>[3–6]</sup> However, whether these back contacts are stable is what one is more concerned with.

Based on the work of predecessors,<sup>[7]</sup> in order to research the contribution of Te:Cu back contact towards deep levels, the CdS/CdTe thin film solar cells with Te:Cu back contact were characterized by deep level transient spectroscopy (DLTS). DLTS is a powerful technique for the identification of deep levels in Schottky barriers and p–n junctions. It offers key information regarding the deep levels including activa-

tion energy, capture cross section, and density.

In the present study, one hole trap H1 and one electron trap E1 are observed respectively. H1 at  $E_v + 0.128$  eV is proved to be the so-called A centre,<sup>[8]</sup> which is due to the vacancy of Cd ( $V_{Cd}$ ) and halogen atoms. E1, localized at 0.178 eV below  $E_c$ , is believed to be correlated with the interstitial  $Cu_i^+$  in CdTe.

## 2. Experiment

The configuration of CdS/CdTe thin film solar cell in our research is described as follows. An  $n^+$ -CdS thin film was grown by chemical-bath deposition (CBD) onto the glass substrate coated with  $SnO_2:F$ . The CdTe layer was then grown by close-space sublimation (CSS). The post-treatment with  $CdCl_2$  at 415 °C for 25 min was used to obtain proper carrier type and increase the size of grains in the CdTe layer. Te:Cu back contact, the essential layer in solar cell device structure, was deposited on the CdTe surface by co-evaporation.<sup>[9]</sup> The Te/Cu ratio was 1:2. And then the device was treated in a pure  $N_2$  ambient at about 180 °C. Finally a thin layer of Au was applied. The effective area of the cell was measured to be 12.56 mm<sup>2</sup>.

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Semilab. Prior to the experiment, cells were kept in the dark chamber for at least half an hour to acquire stable capacitance. Capacitance–voltage ( $C$ – $V$ ) measurement was conducted to determine the doping concentration ( $N_D$ ) and built-in voltage ( $U_B$ ). In the case of p–n junctions, the calculated  $N_D$  was the doping concentration of more weakly doped side (CdTe thin film in our study). Both  $N_D$  and  $U_B$  were used in calculating the deep level concentration  $N_T$ . The DLTS measurements (Temperature-scan) were performed between 80 K and 320 K at a constant heating rate of 0.5 K/s. After performing and evaluating several measurements, the Arrhenius plots were given. They were fitted by the straight line equation,

$$\ln(T^2/e) = -\ln(K\sigma) + E_T/KT, \quad (1)$$

where  $e$  is the emission rate for a relevant trap. The slope of the line determines the activation energy  $E_T$ .

Isothermal DLTS (ITS) was also executed (temperature is kept constant while frequency is being scanned). With its high scanning rate, we could focus on a narrow temperature range to test the samples many times.

It was found experimentally that the repeating cooling and voltage bias applied to the samples would lead to a degradation of their characteristics.<sup>[10]</sup> Table 1 shows the observed cell behaviours before and after the DLTS measurements.

**Table 1.** Solar cell parameters before and after the DLTS measurements.

	$\eta/\%$	FF/%	$V_{oc}/mV$	$J_{sc}/mA \times cm^{-2}$
initial	6.33	38.64	687	23.84
after 1st run	6.27	37.55	683	25.31
after 2nd run	5.65	36.17	688	20.30

### 3. Results and discussion

#### 3.1. $C$ – $V$ measurement

The doping concentration  $N_D$  is obtained from  $C$ – $V$  measurement at room temperature in the dark according to the following equations:

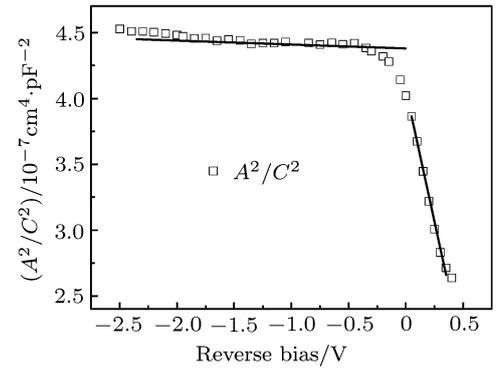
$$C_0^2 = \Delta V_R / \Delta(1/C^2), \quad (2)$$

$$N_D = 2C_0^2 / A^2 \varepsilon q, \quad (3)$$

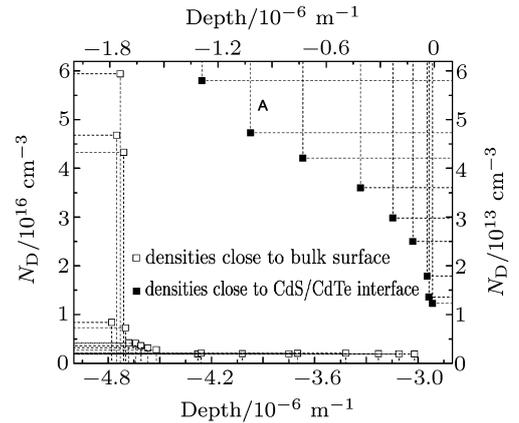
where  $A$  is the effective area,  $\varepsilon$  is the dielectric constant, and  $V_R$  is the reverse bias.

The curve for  $(A^2/C^2)$  versus  $V_R$  is shown in Fig. 1. There are two distinct slopes. The calculated

doping densities deduced from  $(A^2/C^2)$  versus  $V_R$  are  $5.97 \times 10^{16}/cm^3$  at large reverse bias, which is associated with bulk doping, and  $1.35 \times 10^{13}/cm^3$  at forward bias, which corresponds to the region near CdS/CdTe interface. As seen from the non-linearity of  $(A^2/C^2)$  versus  $V_R$  curve, we obtain a variable doping concentration as a function of depth. Figure 2 displays the doping densities profile. The concentration reduces three orders of magnitude from the region near bulk surface to CdS/CdTe interface. This reduction in doping density profile suggests a high density of interface states resulting from compensation at the CdS/CdTe junction.<sup>[11]</sup>



**Fig. 1.**  $(A^2/C^2)$  vs.  $V_R$ . (Here  $V_R$  denotes reverse bias).



**Fig. 2.** Depth profile of doping densities in the CdTe layer, derived from the data in Fig. 1.

#### 3.2. DLTS measurements

It is assumed in discussing the DLTS data that the CdS layer is highly doped, so the depletion region is within the p–CdTe.<sup>[12]</sup> In this context, therefore, a majority carrier trap is a hole trap corresponding to a negative peak in the DLTS spectrum; a minority carrier trap is an electron trap corresponding to a positive peak in the DLTS spectrum.

Figure 3 shows the DLTS spectra at three different frequencies, i.e. 500, 1500 and 2500 Hz, separately. Samples tested at a reverse bias of  $-0.4$  V, with a pulse amplitude of  $0.6$  V and pulse duration of  $16 \mu\text{s}$ . Two main DLTS peaks are discovered in a temperature range of  $140\text{--}320$  K. Because of the freeze-out of capacitance, no peaks could be observed below  $140$  K. Level H1, localized at  $E_v + 0.128$  eV, is considered to originate from the so-called A centre in CdTe, consisting of a vacancy at a Cd site and a halogen atom on a Te site,<sup>[13]</sup> particularly in the  $(V_{\text{Cd}}\text{--}Cl_{\text{Te}})$  complex. This centre plays a significant role in the compensation process of CdTe:Cl as it neutralizes the  $V_{\text{Cd}}$  native acceptor.<sup>[14]</sup> Level E1, localized at  $E_c - 0.178$  eV, is believed to be induced by Cu impurities. It is demonstrated that Cu impurities diffuse into the CdTe thin film during and after back contact formation.<sup>[15]</sup> Though the fundamental understanding of E1 is unclear, it is learned that the E1 is largely correlated with the interstitial  $\text{Cu}_i^+$  in CdTe based on former evidence.<sup>[16]</sup> The trap information derived from the Arrhenius plots (Fig. 4) is summarized in Table 2. We can see that the capture cross section and deep level concentration are extremely small.

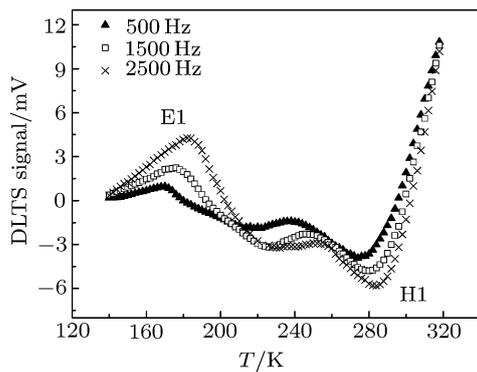


Fig. 3. DLTS spectra at three different frequencies.  $U_R = -0.4$  V,  $U_{\text{plus}} = 0.6$  V, pulse duration= $16 \mu\text{s}$ .

It implies that the trapping effect of these deep levels is not prominent.

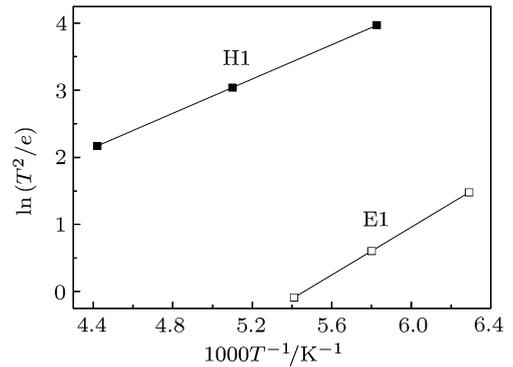


Fig. 4. Arrhenius plots of deep levels in CdS/CdTe solar cells.

During the experiment, setting reverse bias was crucial to the obtaining of the diagrams of DLTS measurements. As seen from Fig. 5, the DLTS peaks at reverse bias  $-0.8$  V are much flatter than the ones at reverse bias  $-0.4$  V. Through comparing two curves in Fig. 5, what deserves our attention is whether there is a shoulder peak on the left of H1 peak. In order to seek the key to our doubt, isothermal DLTS (ITS) was performed.

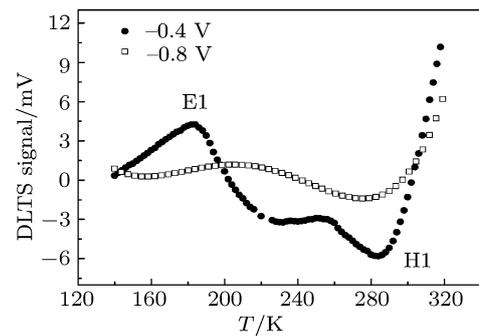


Fig. 5. DLTS spectra at two different reverse biases.

Table 2. DLTS data of CdS/CdTe solar cells with Te:Cu back contact.

trap levels	activation energy ( $E_T$ /eV)	capture cross section ( $\sigma/\text{cm}^2$ )	deep level concentration ( $N_T/\text{cm}^{-3}$ )
H1	$E_v + 0.128$	$2.19 \times 10^{-19}$	$1.50 \times 10^{10}$
E1	$E_c - 0.178$	$7.80 \times 10^{-19}$	$8.53 \times 10^{10}$

### 3.3. ITS measurements

Isothermal DLTS (ITS) offers a distinct advantage as a narrow temperature range can be scanned many times to extract the information of deep defects with high scanning rate.

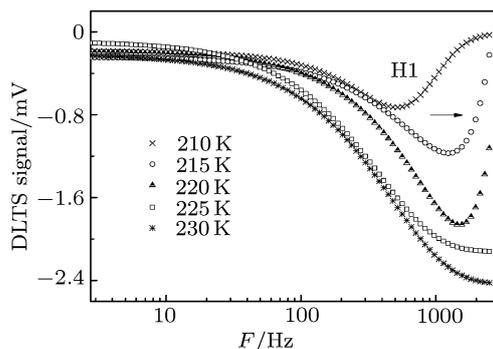


Fig. 6. Isothermal DLTS (ITS) data of level H1.

ITS measurements were performed in steps of 5 K between 200 K and 290 K. Figure 6 shows the spectra of level H1 fitting of the data to Gaussian function.<sup>[17]</sup> From the figure we can see clearly that the H1 peak

shifts rightwards as temperature rises. However, it is failed to find any other peak between 200 K and 240 K. It demonstrates that there exists only H1 peak without any shoulder peak.

## 4. Conclusion

CdS/CdTe thin film solar cells with Te:Cu back contact are characterized by DLTS and ITS. Two deep levels are observed. It is found that back contact induces Cu impurities, which corresponds to level E1 localized at  $E_c - 0.178$  eV. The other trap H1 localized at  $E_v + 0.128$  eV is the so-called A centre. Both of them are probably important for the solar cells characteristics.

## References

- [1] Capper P 1994 *Properties of Narrow Gap Cadmium-Based Compounds* (Volume 10) (London: IEE) p. 591
- [2] Chu T L and Chu S S 1995 *Solid-State Electron* **38** 533
- [3] Rose D H, Hasoon F S, Dhere R G, Albin D S, Ribelin R M, Li X S, Mahathongdy Y, Gessert T A and Sheldon P 1990 *Progress in Photovoltaics: Research and Applications* **7** 331
- [4] Li W, Feng L H, Zhang J Q, Wu L L, Cai Y P, Zheng J G, Cai W, Li B and Lei Z 2008 *Sci. Chin. Ser. E: Technological Sciences* **51** 33
- [5] Hegedus S S, McCandless B E and Birkmire R W 2000 *Proc. 28th IEEE PVSC* 535
- [6] He J X, Zheng J G, Li W, Feng L H, Cai W, Cai Y P, Zhang J Q, Li B, Lei Z, Wu L L and Wang W W 2007 *Acta Phys. Sin.* **56** 5548 (in Chinese)
- [7] Li B, Liu C, Feng L H, Zhang J Q, Zheng J G, Cai Y P, Cai W, Wu L L, Li W, Lei Z, Zeng G G and Xia G P 2009 *Acta Phys. Sin.* **58** 1987 (in Chinese)
- [8] Allen J W 1995 *Semicond. Sci. Technol.* **10** 1049
- [9] Li W, Feng L H, Wu L L, Cai Y P, Zhang J Q, Zheng J G, Cai W, Li B, Lei Z and Zhang D M 2005 *Acta Phys. Sin.* **54** 1879 (in Chinese)
- [10] Komin V, Viswanathan V, Tetali B, Morel D L and Ferikides C S 2002 *Proc. 29th IEEE PVSC* 736
- [11] Balcioglu A, Ahrenkiel R K and Hasoon F 2000 *J. Appl. Phys.* **88** 7175
- [12] Lourenço M A, Yew Y K, Homewood K P, Durose K, Richter H and Bonnet D 1997 *J. Appl. Phys.* **82** 1423
- [13] Castaldini A, Cavalini A and Fraboni B 1996 *Appl. Phys. Lett.* **69** 3510
- [14] Castaldini A, Cavallini A, Fraboni B, Fernandez P and Piqueras J 1998 *J. Appl. Phys.* **83** 2121
- [15] Lyubomirsky L, Rabinal M K and Cahen D 1997 *J. Appl. Phys.* **81** 6684
- [16] Romero M J, Albin D S, Al-Jassim M M, Wu X Z, Moutinho H R and Dhere R G 2002 *Appl. Phys. Lett.* **81** 2962
- [17] Versluys J, Clauws P, Nollet P, Degraeve S and Burgelman M 2004 *Thin Solid Films* **451** 434