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Identification of deep level defects in CdTe solar cells using transient photo capacitance spectroscopy

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Abstract

Here we present a study on the characterization of deep level defects in CdTe thin film solar cells by transient photo capacitance measurement. A broad defect band centered at around 1.07 eV above the valance band was detected at 80 K. The temperature dependent transient photo capacitance reveals fast signal quenching of this defect, which suggests that this deep level defect might work as an effective recombination center to affect the device performance.

1. Introduction

As one of the most successful commercial applications of thin film solar cells, CdTe-based photovoltaics are rapidly developed in recent years. The record efficiency of lab-scale CdTe solar cells already hit 22.1%. However, in the state-of-the-art CdTe solar cells, the open circuit voltage (V_{OC}) was only 880 mV, which was only 76.1% of the Shockley-Queisser (SQ) limit of 1157 mV[1)]. In comparison, highly efficient GaAs device has achieved 97.7% of the SQ limit with a similar band gap[2)]. The lower carrier lifetime is considered responsible for the V_{OC} deficit in CdTe based photovoltaics. Normally, the carrier lifetimes are mainly limited by the defect mediated recombination. Thus, identifying deep level defects in CdTe absorber layer, and understanding the recombination mechanism are crucial for further optimization of the performance of the solar cells.

Various studies have been carried out to explore the defect properties both in experiment and simulation methods. Based on the first principles calculations, Wei et al suggested that the dominant recombination centers are the Te anti-site (Te_{Cd}) and Te interstitial (Te_i) in CdTe[3)]. Photoluminescence, cathodoluminescence, deep level transient spectroscopy etc. have been utilized to study the properties of the defect in CdTe. Nevertheless, the physical nature of the defects has not been clearly understood thus far. Consequently, it is still difficult to identify the deep levels and understand the mechanisms of recombination as well as the dynamics of the charged carriers in the devices. With the sub bandgap monochromatic irradiation to excite the emission process of the deep levels, the transient photo capacitance (TPC) spectroscopy is effective for the detection of the deep level defects. In this study, a deep level in CdTe was detected by TPC measurement. The probable recombination process via this deep defect was identified and temperature dependent TPC was carried out to trace the recombination process.

2. Experimental Details

The superstrate-configurated CdTe solar cells (Tec 12D/CdS/CdTe/ZnTe:Cu/Au) were fabricated. The ~55 nm thick CdS was deposited by chemical bath deposition. After that, polycrystalline CdTe thin film was then prepared by close space sublimation followed by $CdCl_2$ activation. Prior to the deposition of ZnTe:Cu back contact layer, bromine methanol solutions etching was carried out to remove the oxides on the surface. Then the back contact was prepared by evaporation. Full structured device with an accurate area of 0.24 cm^2 was achieved by deposition of Au contacts and laser scribing separation. The efficiency of this device is determined by light current-voltage characterization to be 15.2% with open circuit at 818 mV short circuit current density at 25.36 mA/cm^2 under AM 1.5 illumination. Detailed information of the device fabrication process, please refer to our previous publications[4)].

The TPC measurement was performed by using a halogen lamp and a monochromator as light source in the cryostat cooled by liquid nitrogen. The capacitance transients were recorded after a fill pulse of 0 V to a quiescent bias of -0.5 V in both dark and illumination conditions by an ultra-fast capacitance meter. The light pulse was generated by an electronic shutter with frequency at 0.5 s^{-1}. Monochromatic light intensity was reduced by ND filters and the intensity of the light was measured by Ge Photodiode and the photon flux reaching the sample surface was on the order of 10^{15} photons/(cm^2s). The detailed setups of the TPC system could be found in our previous research[5)].

3. Results and Discussion

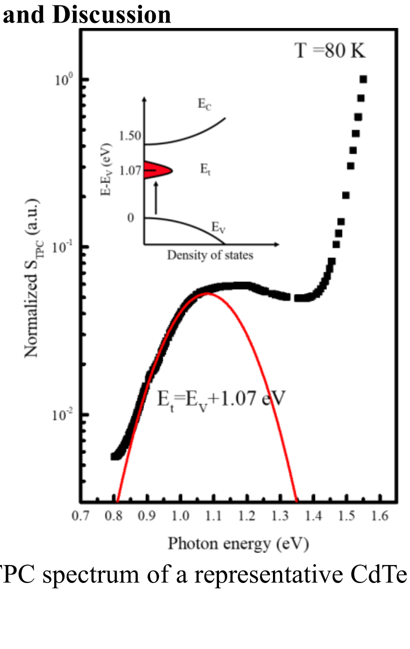

Fig. 1. TPC spectrum of a representative CdTe solar cell

measured at 80 K. The red line indicates the fitted data using a Gaussian shaped defect band.

The TPC spectrum for a representative CdTe device at 80 K is shown in Fig. 1. The TPC signals have already normalized by the photon flux in the entire spectrum. For the CdTe device, the spectra show two optical absorption characters. First is the inter-band absorption with photon energy close to or higher than the CdTe bandgap and second is the sub-bandgap absorption by the defect states. For the photons with energy close to the bandgap of CdTe, the increased TPC signals almost show an exponential relationship with the photon energy, which is also corresponding to light absorption of direct band gap materials. The carrier transitions between the valance band (E_V) and conduction band (E_C) contribute to the TPC signals. As for the sub-bandgap absorption, the TPC signals normally originate from the carrier transitions between band edges and defect states under monochromatic light illumination. The positive TPC signals indicate that the emission of holes from the trap states to valance band shrinks the depletion region increasing the capacitance. Fitted by Gaussian equation, an abroad defect is identified to be 1.07 eV above the valence band maximum.

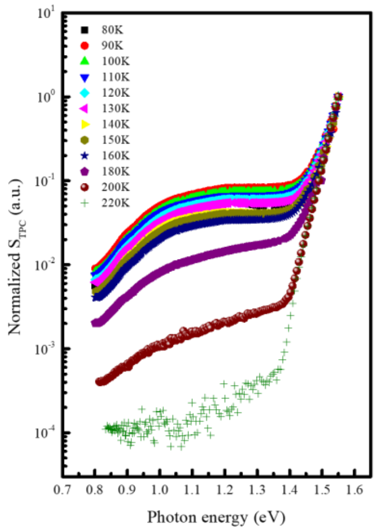

Fig. 2. TPC spectra of CdTe solar cell in the temperature range from 80 to 220K

According to the Shockley recombination theory[6], the recombination rate via defect is described as follows:

$$U = \frac{N_t \sigma v_{th}(np - n_i^2)}{p + n_i \exp(\frac{E_t - E_i}{k_0 T})} \quad (1)$$

Where the N_t is the defect density, n (p) is the electron (hole) density, n_i is the intrinsic carrier density, σ is the defect capture cross section, v_{th} is the thermal carrier velocity, E_t is the defect level and E_i is the intrinsic fermi level. From this, one may notice that when $E_t=E_i$, the recombination velocity attains maximum. Deep levels are more likely to contribute to carrier recombination. The defect type also plays an important role in the carrier recombination because it greatly affects σ. According to the previous simulation, this defect may assign as Te anti-site (Te_{Cd}(2+/+)) defect which was located at 1.02 eV above the E_V and suggested as the possible recombination centers limiting the minority carrier lifetime[3]. If so, the deep levels detected here belong to donor like defects. Due to coulomb attraction, the donor type defects are assumed to have strong interaction with the electrons in CdTe, engendering very large electron capture cross section. In summary, this deep defect detected here may act as donor like defect and limit the carrier lifetime in CdTe.

Temperature dependent TPC spectra from 80 to 220 K for CdTe devices is shown in Fig. 2. It is obvious that the defect signal in the sub-bandgap region decreases with an increase in the temperature. However, this variation is not observed in the inter band absorption region in this temperature range. Such kind of variation in TPC signal in the sub band gap region is induced by fast charge relaxation process from the defect states to the E_V. Increasing the temperature would directly accelerate the de-trapping process due to enhanced rate of emission at higher temperature. The fast quenching in the defect signal also indicates that it is highly probable to act as an effective recombination center. Further research exploring the recombination mechanism via this defect is underway.

4. Conclusions

A broad defect band centered at around 1.07 eV above the valance band was detected by transient photo capacitance measurement in CdTe solar cells. Recombination process via this deep defect was explored by temperature dependent transient photo capacitance. The defect signals of this deep levels are quenched by increasing temperature. The fast quenching defect signal indicates it a probable effective recombination center. This deep defect band may relate to the Te anti-site defects and further research exploring its origination is significant in device performance and still on the way.

Acknowledgements

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References

1) W. Shockley and H.J. Queisser: J. Appl. Phys. **32** [3](1961)510.
2) G.M. Wilson, M.M. Al-Jassim, W.K. Metzger, S.W. Glunz, P. Verlinden, X. Gang, L.M. Mansfield, B.J. Stanbery, K. Zhu, Y. Yan, J.J. Berry, A.J. Ptak, F. Dimroth, B.M. Kayes, A.C. Tamboli, R. Peibst, K.R. Catchpole, M. Reese, C. Klinga, P. Denholm, M. Morjaria, M.G. Deceglie, J.M. Freeman, M.A. Mikofski, D.C. Jordan, G. TamizhMani and D.B. Sulas: J. Phys. D: Appl. Phys. (2020).
3) T.A. Gessert, S.H. Wei, J. Ma, D.S. Albin, R.G. Dhere, J.N. Duenow, D. Kuciauskas, A. Kanevce, T.M. Barnes, J.M. Burst, W.L. Rance, M.O. Reese and H.R. Moutinho: Sol. Energy Mater. Sol. Cells. **119** (2013)149.
4) S. Ren, H. Wang, Y. Li, H. Li, R. He, L. Wu, W. Li, J. Zhang, W. Wang and L. Feng: Sol. Energy Mater. Sol. Cells. **187** (2018)97.
5) T. Sakurai, H. Uehigashi, M.M. Islam, T. Miyazaki, S. Ishizuka, K. Sakurai, A. Yamada, K. Matsubara, S. Niki and K. Akimoto: Thin Solid Films. **517** [7](2009)2403.
6) W. Shockley and W.T. Read: Phys. Rev. **87** [5](1952)835.