



Roll-over behavior in current-voltage curve introduced by an energy barrier at the front contact in thin film CdTe solar cell



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ABSTRACT

Roll-over phenomenon in the current–voltage (J–V) curve is often observed in a CdTe thin film solar cell. The roll-over phenomenon, which is occurred near the open-circuit voltage in a light J–V curve, is due to Schottky energy barrier formed at the CdTe/metal interface in a CdTe solar cell back contact. In this study we report a J–V roll-over phenomenon which is induced by an energy barrier at the front contact of a CdTe solar cell. Two kinds of oxides, namely, Al₂O₃ and SnO₂, were deposited as high-resistance transparent (HRT) layer between the window layer CdS and the fluorine doped tin oxide (FTO) front electrode in CdTe solar cells. These two oxides present much different electronic band alignment with FTO and CdS. SnO₂ formed almost no energy barrier with CdS, this allowed smooth transport for photo-generated electrons from CdTe to CdS and FTO. However, Al₂O₃ formed a high energy barrier with CdS. The rather high energy barrier with a value of 3.43 eV at the CdS/Al₂O₃ interface induced a J–V roll-over phenomenon in a CdTe thin film solar cell, which dramatically led to a quick decrease for the cell device efficiency. The electron transport at the FTO/Al₂O₃/CdS interface is governed by tunneling effect. The results presented in this study demonstrate that the band structure at the front electrode plays an important role for the performance of a CdTe thin film solar cell.

1. Introduction

CdTe is an efficient photovoltaic material with a direct band gap of 1.45 eV and an absorption coefficient as high as 10^5 cm^{-1} for the photons with energy higher than the band gap (Myers et al., 1981). The world-record efficiency of research scale CdTe solar cell and large area module have reached 22.1% and 18.6%, respectively (Green et al., 2015). CdTe thin film solar cell has quickly become a competitive product in the photovoltaic market. Despite the impressive cell efficiency increase made in the last several years, there are still some key issues to be solved or deeply studied. CdTe has a high work function of $\sim 5.7 \text{ eV}$, which is higher than that of all the common metals used as metal contacts. Thus, roll-over phenomenon in the current–voltage (J–V) curve is often observed in a CdTe solar cell. The roll-over phenomenon, which is occurred near the open-circuit voltage in a light J–V, is induced by the Schottky energy barrier formed at the CdTe/metal interface (Niemegeers and Burgelman, 1997; Corwine et al., 2004). A two-diode model has been proposed to explain the roll-over behavior and estimate the contact barrier height (Niemegeers and Burgelman, 1997; Demtsu and Sites, 2006; Koishiyev et al., 2008).

However, not all roll-over phenomena observed were introduced by a back contact barrier. Kephart et al. (2016) have shown that a roll-over phenomenon in J–V would appear when there is a relatively large positive conduction band offset (CBO), which is also called spike band offset, at the interface of a window layer and the absorber CdTe film.

CdS is widely adopted as the window layer for thin film CdTe solar cell fabrication, therefore the light photons having a wavelength below 515 nm would be strongly absorbed by CdS window layer (Yang et al., 2014). Using a relatively thin CdS layer is one approach to enhance the short-circuit current density (J_{SC}). However, this approach faces significant challenges. As the thickness of CdS is reduced, open-circuit voltage (V_{OC}) and fill factor (FF) will inevitably be decreased because of the electric shorting and pinholes developed at the CdS/CdTe diode junction (Yang et al., 2014). To avoid the adverse impact caused by decreasing the thickness of CdS, a front buffer layer, also called high-resistance transparent (HRT) layer, is usually deposited between the transparent conducting oxide (TCO) electrode and a CdS window layer (Ferekides et al., 2005). Several materials such as SnO₂, ZnO, In₂O₃ and Zn₂SnO₄, have been employed as an HRT layer (Niles et al., 1993; Liu et al., 2012; McCandless and Dobson, 2004; Wu, 2004). Not all resistive

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oxides are effective HRT layers. The band alignment of an HRT layer with both the CdS and the front electrode must be aligned in a way to allow the photo-generated electrons to transport almost barrierlessly to the collecting electrode. In principle, mismatching in band alignment at the front electrode interface will introduce an energy barrier for electron transport and thus increase the cell series resistance. In this study, a comparative study has been carried out to study the effect of the band alignment at the front electrode on the carrier transport in CdTe solar cells. Al₂O₃ and SnO₂ thin films were deposited as HRT layers between FTO electrode and a CdS window layer. SnO₂ has a similar electronic band structure as that of fluorine doped tin oxide (FTO), therefore, SnO₂ is an efficient HRT layer for CdTe solar cell fabrication. Al₂O₃, on the other hand, presents a much different electronic band alignment with that of FTO and CdS. We suggest that the band alignment at the front electrode of a CdS/CdTe solar cell has a relatively large effect on the photo-generated electron transport.

2. Experimentals

The CdTe solar cells fabricated in this study had a structure of glass/FTO/HRT/n-CdS/p-CdTe/Cu: Au back electrode. Al₂O₃ and SnO₂ films were deposited on glass/FTO substrates (14 Ω/sq, made by Nippon Sheet Glass Co. Ltd.) by the RF magnetron-sputtering technique, respectively. Al₂O₃ and SnO₂ targets of 99.99% purity were used in this work and the deposition atmosphere was a mixture of O₂ and Ar with a total pressure of ~1.1 Pa. The ratio of O₂ was 20% in order to compensate the loss of oxygen during sputtering. N-type CdS window layers with a thickness of about 70 nm were prepared on glass/FTO and glass/FTO/Al₂O₃ or SnO₂ substrates by chemical bath deposition (CBD) technique (Yang et al., 2014). P-type CdTe absorber layers were deposited on CdS layers by close-spaced sublimation technique (CSS) in a homemade film-deposition system. Then, the CdS/CdTe heterojunctions were activated with the presence of CdCl₂ in the air atmosphere. After being etched in nitric-phosphoric (NP) solution, Cu/Au bilayer back contacts were evaporated on the CdTe films by vacuum evaporation. The schematic structure of CdTe thin film solar cell in this study is shown in Fig. 1a.

X-ray photoelectron spectroscopy (XPS) measurements were performed using a Thermo VG Scientific ESCALAB 250 instrument with Al Kα as the X-ray source. All the XPS spectra were calibrated by using the carbon 1s energy level (284.80 eV). The solar cell current–voltage (J–V) curves were measured under the standard AM1.5 illumination (1 kW/m², 25 °C) using a solar simulator (Oriol Sol 3A, USA).

3. Results and discussions

Fig. 1a shows the schematic CdTe solar cell structure fabricated in this study. Fig. 1b and c show the light J–V curves of CdTe solar cells with an Al₂O₃ and a SnO₂ HRT layer, respectively. The two kinds of solar cells, we call the Al₂O₃ and the SnO₂ solar cell hereafter in this

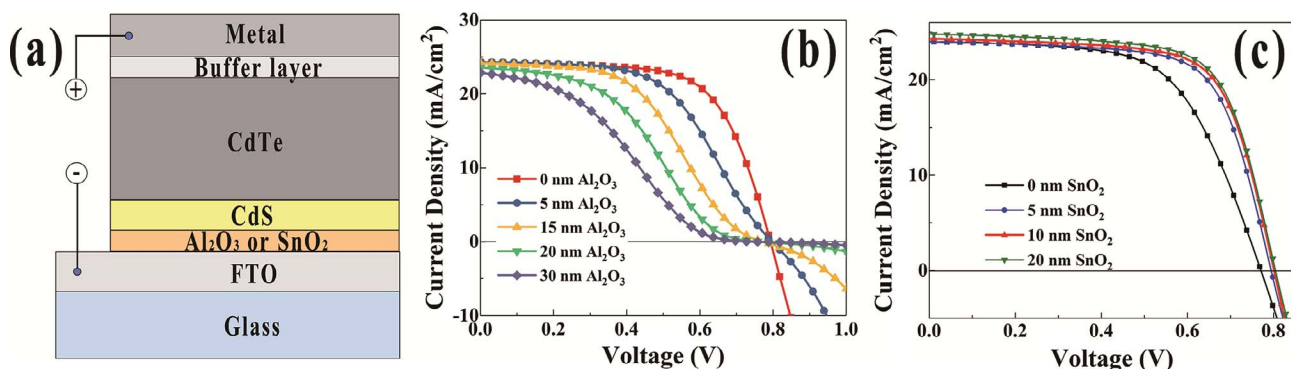


Fig. 1. (a) Schematic structure of CdTe solar cells fabricated in this study; light J–V curves of CdTe solar cells with different HRT thickness of (b) Al₂O₃ and (c) SnO₂.

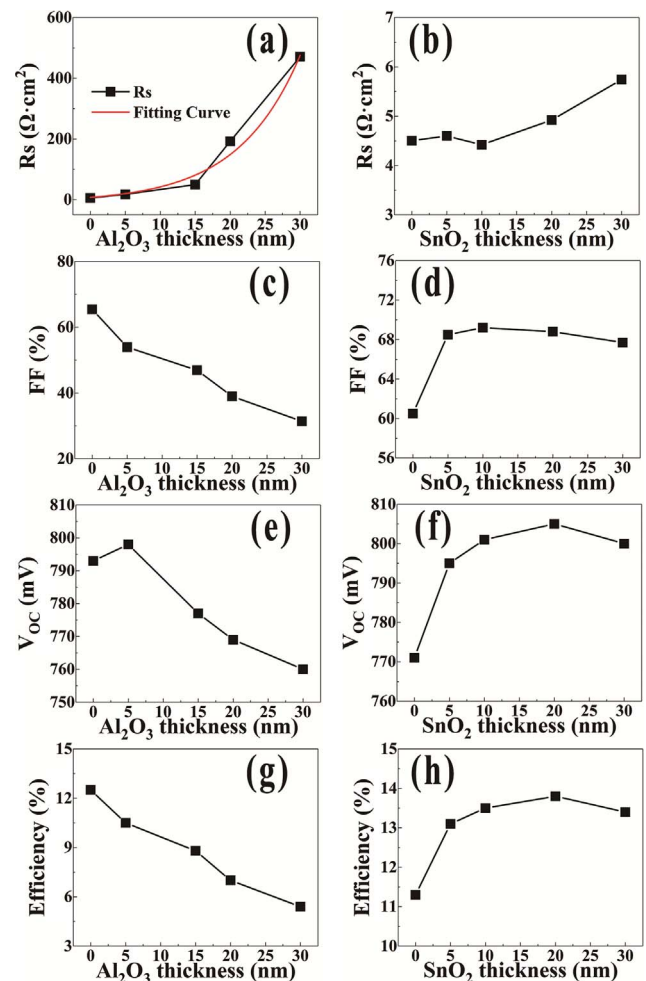


Fig. 2. CdTe solar cell device parameters versus the Al₂O₃ or the SnO₂ HRT layer thickness. (a), (b) series resistance R_s ; (c), (d) fill factor (FF); (e), (f) open-circuit voltage (V_{OC}); (g), (h) cell efficiency.

study, demonstrated much different J–V curve shape with increased Al₂O₃/SnO₂ HRT layer thickness. The dependence of cell device parameters on the Al₂O₃/SnO₂ HRT thickness is shown in Fig. 2. It can be seen that compared to the cell without a SnO₂ HRT layer, the cells with the insertion of a SnO₂ HRT layer demonstrated significant increase in the open-circuit voltage (V_{OC}) and the fill factor (FF), see Fig. 2d and f. The V_{OC} was improved from 771 to 805 mV for the cells without and with a 20-nm-thick SnO₂ buffer layer, respectively. The FF was increased from 60.5 to 69.2% for the cells without and with a 10-nm-thick SnO₂ buffer layer, respectively, as can be clearly seen in Fig. 2d. The improvement of the FF was mainly contributed by the much

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