J Mater Sci: Mater Electron (2009) 20:661–665
DOI 10.1007/s10854-008-9782-2

Influence of SnO_2 films with high resistance on the performance of CdTe solar cells

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Received: 16 February 2008 / Accepted: 15 July 2008 / Published online: 26 August 2008

Abstract In this paper, we report the SnO_2 thin films with high resistance prepared by magnetic reactive sputtering on the transparent conductive glass covered with SnO_2:F layers, and study the structural, optical, and electrical properties of the films before and after annealing, as well as the influence of the annealing on the performance of CdTe solar cells. The results have shown that SnO_2 thin films almost have the same structure as SnO_2:F, and SnO_2 high resistance transparent (HRT) insertion layer between transparent conductive oxide (TCO) and CdS affects little on light transmittance. After introducing the HRT layer, the tunneling leakage caused by the pinholes can be avoided, which effectively protects the *p*–*n* junction (Wu et al. Proceedings of NCPV program review meeting AIP, New York, 22–26, 2001). Meanwhile, higher parallel resistivity, fill factor (FF), short-wave response, carrier concentration, and lower dark saturation current density have been achieved. As a result, the conversion efficiency is improved by 14.5%, from 10.3% to 11.8%.

1 Introduction

For recent years, CdTe solar cells have been developing very quickly as a promising photovoltaic material. The highest conversion efficiency of the solar cells with the area of 1 cm^2 has been 16.5% [1]; and in 2001, we fabricated the cells with the efficiency of 13.38%. However, it is still much lower than the theoretical value of 28%. To improve the conversion efficiency, much work has been done to optimize the cell structure. Batzner and Romeo [2] developed the solar cells with the efficiency of 12.5% using Sb/Au films as the back contact for the first time; Shao [3] effectively modified band structure and significantly improved the conversion efficiency with $Cd_{1-x}Zn_xTe$/ZnTe:Cu as the back contact; and Li Wei [4] introduced CdS_xTe_{1-x} films as the transition layer.

In the solar spectrum, radiant intensity of the light wave with the wavelength between 300 nm and 550 nm accounts for 26.3%. So it is important to improve the short-wave response of the solar cells. Then CdS layer must be reduced because it blocks and absorbs light wave less than 500 nm wavelength. When the thickness of CdS films is less than 100 nm, it will significantly enhance short-wave response. At the same time, however, pinholes will take on in the thin CdS films, which makes CdTe contact directly with TCO, damaging *p*–*n* junctions, and impacting on short-current (J_{SC}) and on FF.

In order to overcome the drawbacks above, between TCO and reduced CdS layer, a SnO_2 HRT layer was introduced. In the paper, we study the influence of the introduction of the SnO_2 HRT layer.

2 Experiments

2.1 Preparation

In this paper, we prepared the solar cell A without HRT, and the cell B with HRT. The structure of the cell B is Glass/TCO/HRT/CdS/CdTe/ZnTe:Cu/Ni (Fig. 1).

ITO-coated glass substrates, sheet resistance (R_{sh}) < 14 Ω/□ with about 80% light transmission, were obtained from LOF Corporation. The SnO_2 HRT films with

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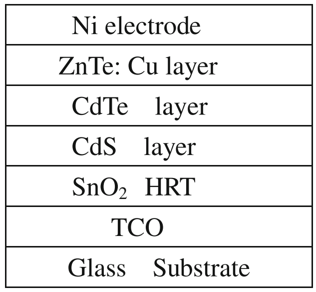

Fig. 1 Structure of the solar cell B

Table 1 Samples and annealing conditions

Number	Annealing conditions	Sample structures
1#	Not annealed	Normal glass
2#	Not annealed	SnO_2:F
3#	Not annealed	SnO_2:F + SnO_2
4#	Vacuum, 500 °C, 40 min	SnO_2:F + SnO_2
5#	N_2, 500 °C, 40 min	SnO_2:F + SnO_2
6#	Atmosphere, 500 °C, 40 min	SnO_2:F + SnO_2

the thickness of 120 nm, $R_{sh} > 20\ \Omega/\square$, and >85% light transmission, were prepared by magnetron sputtering at the atmosphere of oxygen and argon (Ar/O2) [5, 6]. The preparation of CdS and CdTe films is referred in the interrelated articles [7–9].

Annealing conditions for different samples are depicted in Table 1.

2.2 Test instruments

The X-ray diffraction (XRD) measurement was performed with a DX-1000 diffractometer using Cu $K\alpha$ radiation. The atomic force microscope (AFM) was measured by Seiko SPA400 from Japan. The transmittance spectrum of the thin films was tested using UV-2100 spectrophotometer of Shimadzu Corporation. Illuminated *I–V* measurements were performed with Solar Cell *I–V* Characteristics Tester. Dark *I–V* and $1/C^2-V$ Characteristics were studied using Semiconductor Characteristics Tester (4155C and 4284A respectively).

3 Results and discussion

3.1 Structure and morphology

In order to find the structure changes of the films after depositing SnO_2, XRD patterns of the different samples were tested (shown in Fig. 2).

Figure 2 shows that there is the highest diffraction peak in the (200) crystal face, with a preferred orientation; and,

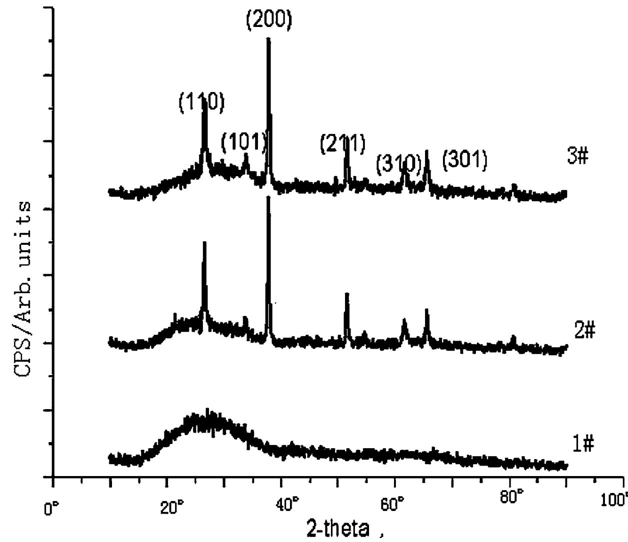

Fig. 2 XRD patterns of the samples

there are strong diffraction peaks in the (110), (101), (211), (310), and (301) crystal faces. After calculating, we find that the lattice constants are closely similar to each other (SnO_2:F: $a = b = 0.475523$ nm, $c = 0.320145$ nm; SnO_2: $a = b = 0.475$ nm, $c = 0.320197$ nm), with few interface states [10]. It illuminates that SnO_2 thin films almost have the same structure as SnO_2:F.

For the different preparation conditions for SnO_2:F films and SnO_2 films, and the following process for the cells at high temperature, the SnO_2 films were annealed at 500 °C under different atmospheres. Then the HRT layer after annealing was studied.

Figure 3 shows the impact of annealing at 500 °C under different atmospheres on the samples. As shown in Fig. 2, the relative strength of the different diffraction peaks is changed after annealing at 500 °C, but their positions change little. Besides, the different annealing atmospheres at the same temperature have little impact on the structure and other physical properties of the films.

Figure 4 shows the morphology of the surface of the SnO_2 films before and after annealing. It illuminates that the film quality is improved significantly and the HRT layer becomes much denser and uniformer as a result of SnO_2 grains grow up after annealing. Also, grains growing up results in the preferred orientation, making the relative strength of the diffraction peaks of the films changes, which well agree with the XRD results.

3.2 Transmittance

In order to check the impact of the introduction of the HRT layer on the light transmittance, we measured spectrum curves of samples #2, #3, and # 6 (Fig. 5). As shown in

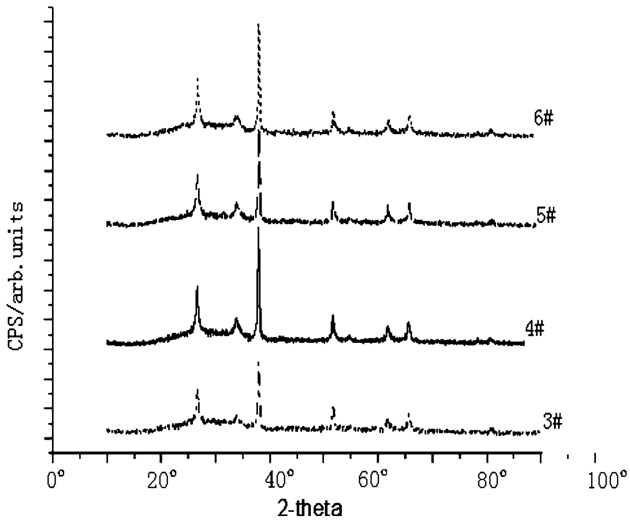

Fig. 3 XRD patterns of the different samples

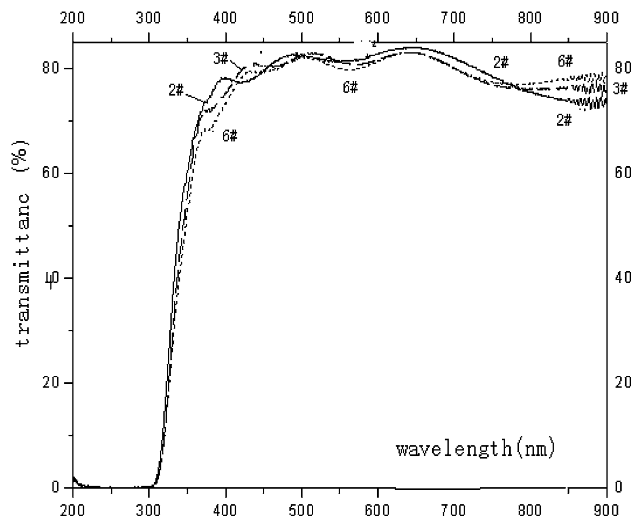

Fig. 5 Spectrum curves of samples #2, #3, and # 6

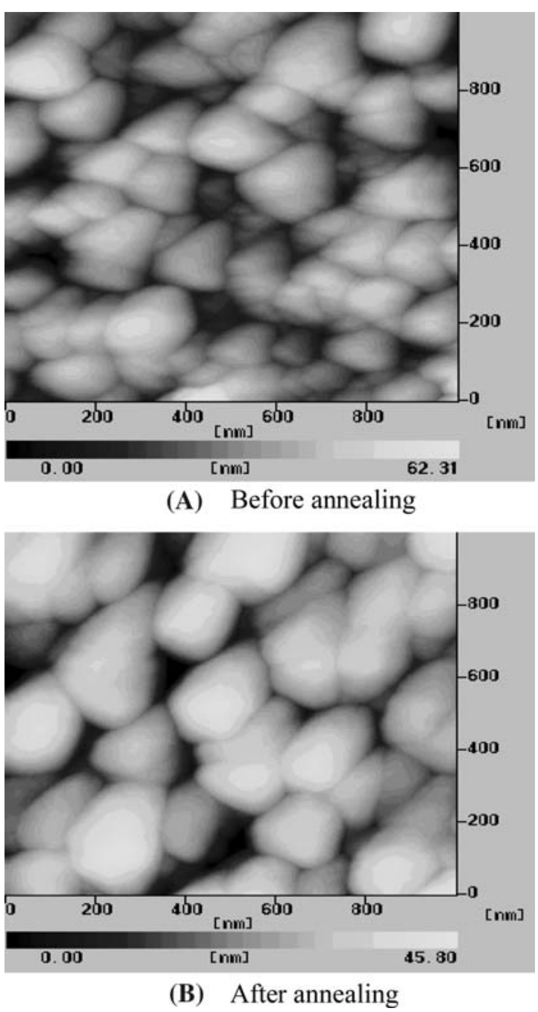

Fig. 4 AFM results before and after annealing

Fig. 5, the transmittance of the SnO_2 films before or after annealing is close to SnO_2:F very much, and will not affect the absorption of the sunlight.

3.3 *C–V* Characteristics

In order to study the influence of the HRT layer on the device performance, we prepared CdTe solar cell A without HRT, and the cell B with HRT. The structure of cell B is according to Fig. 1, and the performance parameter results are shown in Table 2.

Capacitance of solar cells [9, 10] can be expressed as:

$$1/C_{\mathrm{T}}^{2} = 2(V_{\mathrm{D}} - V)/A^{2}\varepsilon_{\mathrm{r}}\varepsilon_{0}qN_{\mathrm{B}}. \quad (1)$$

Its differential coefficient can be described as:

$$\mathrm{d}(1/C_{\mathrm{T}}^{2})/\mathrm{d}V = 2/A^{2}\varepsilon_{\mathrm{r}}\varepsilon_{0}qN_{\mathrm{B}}. \quad (2)$$

Based on the test results, $1/C^2{-}V$ curves are shown in Fig. 6.

Equation 1 shows that there is linear relationship between $1/C^2$ and V. In a given range of bias, the results of experiments well agree with Eq. 1, illuminating that the cells fabricated are greatly close to ideals hetero-junctions.

Impurity concentration N_{B} can be calculated through the Curve slope.

According to the equation [11], the width of the depletion layer can be calculated, too.

$$X_{\mathrm{D}} = A\varepsilon_{\mathrm{r}}\varepsilon_{0}/C_{\mathrm{T}}. \quad (3)$$

After all, the introduction of HRT, perfects the parallel resistance, improves the ideal diode quality factor, changes little in the depletion layer widths, increases the carrier concentration, decreases the dark saturation current density, and improves the performance of the solar cell

Table 2 Performance parameters of the cells

Sample	$X_D/10^{-4}$ cm	$N_D/10^{13}$ cm^{-3}	$J_S/(10^{-9}$ mA/cm$^{2)}$	A	R_s/Ω	R_{sh}/Ω
A	2.8	4.5	8.93	2.12	14	276
B	2.9	6.8	2.08	1.90	6.9	285

Note: X_D—the depletion layer widths; N_D (cm^{-3})—the carrier concentration; J_S (mA/cm^2)—dark saturation current density; A—the diode quality factor; R_s (Ω)—battery connections resistance; R_{sh} (Ω)—battery shunt resistors

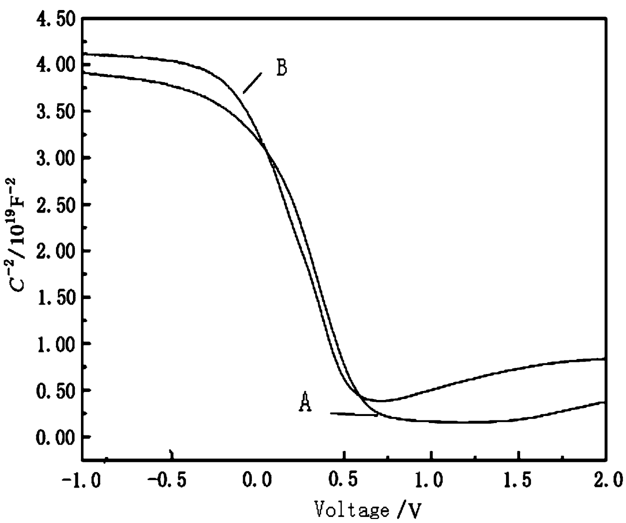

Fig. 6 *C–V* curves of cell A and cell B

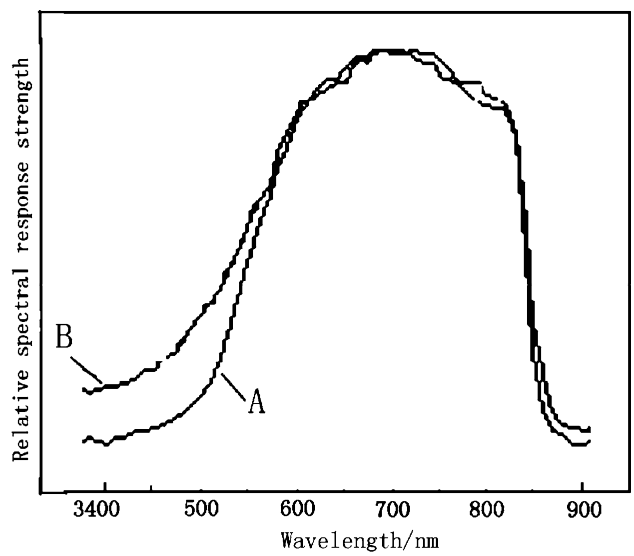

Fig. 7 Spectral response of CdTe solar cells A and B

[12–15]. As a result, the conversion efficiency of cell B achieves 11.8%, increasing by 14.5% compared with 10.3%, the efficiency of cell A.

3.4 Spectral response test

In order to study the influence of the introduction of HRT on the device, we tested the spectral response of the cells A and B (Fig. 7). It shows that the spectral response of cell B is better than cell A, especially in the short-wave region.

On the one hand, HRT, and TCO lattice matching can eliminate from the surface states and other incomplete states resulting in high-speed surface composite. Besides, HRT formed *n*-type ohmic contacts in the CdS area, making more lightly doped in the *n*-type CdS district, and increasing life expectancy and lowering matrix composites, without any additional series resistance.

On the other hand, the introduction of SnO_2 films can enhance inter-diffusion in the CdS/CdTe interface, and weaken the absorption of the short-wave by CdS window layer. Usually, the more photon energy, the lower spectral response. But when the CdS layer is thin enough, the absorption decreases, and the response deadline also moves in the direction of the high-energy (HF). When the thickness of the CdS layer and electron diffusion length can be compared, some carriers in the CdS layer makes diffusion movement to interface, making *p*-type CdTe increasing in the collection, further improving the short-wave spectral response, increasing short-circuit current density, and enhancing the efficiency of the cell [13, 16, 17].

4 Conclusions

1. The intrinsic SnO_2 films with high resistance made by magnetron sputtering almost have the same crystal structure as SnO_2:F. After annealed at 500 °C, SnO_2 grains grow up, the film quality is improved, and the light transmittance of them changes little.
2. Introducing the HRT layer between TCO and CdS during the preparation of CdTe solar cells can effectively protect *p–n* junctions, and improve short-wave response and J_{SC} of the cells.
3. The introduction of the SnO_2 films, lowers the dark saturation current, optimizes the performance of the *p–n* junction, perfects the parallel resistance of the cells, and improves the ideal diode quality factor, the fill factor, as well as the carrier concentration. And the conversion efficiency is improved by 14.5%.

Acknowledgments This work has been supported by National Natural High Technology Research and Development Program (863 program) of the Tenth 5-year Plan of China under grant number 2001AA513010 and University Doctoral Point Foundation (NO. 20050610024). The authors wish to thank Professor Ju-Mu Zhu for his work on XRD measurement.

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