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Highly efficient 1 μm thick CdTe solar cells with textured TCOs

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Abstract

Thickness reduction of CdTe absorption layer down to 1 μm has been achieved by controlling the temperature profile used during the close-spaced sublimation (CSS) growth. Transparent conducting oxides, such as indium tin oxide (ITO) and textured fluorine doped tin oxide (SnO_2:F) films have been investigated as transparent electrodes for such 1-μm-thick CdTe absorption layers to increase the incident light confinement and thus to achieve higher conversion efficiency. The contribution in solar cell performance has been found in the case of textured TCOs with optimum haze ratio (roughness). Conversion efficiencies of 10.6% (V_{oc}: 0.75 V, J_{sc}: 22.02 mA/cm^2, FF: 0.64, area: 1 cm^2) and 11.2% (V_{oc}: 0.78 V, J_{sc}: 22.6 mA/cm^2, FF: 0.63) have been achieved for only 0.6-μm-thick CdTe absorption layers with SnO_2:F-TCO of 11% and 3% of haze ratios, respectively.

Keywords: CdTe; CSS growth; Textured tin oxide (SnO_2:F); ITO

1. Introduction

Cadmium telluride (CdTe) has been well recognized as a very attractive photovoltaic material because of the high potential of several of its properties. The highly efficient cells with the conventional glass/ITO/CdS/CdTe/Cu-doped C/Ag structure are grown to 5–10 μm thick by presently available technologies such as CSS [1]. For further improvement in the open-circuit voltage (V_{oc}) by controlling the

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recombination loss at bulk and to make the CdTe solar cell more attractive for practical use by reducing the material used, the absorption layer of CdTe should be minimum. The minimum thickness for the CdTe film to directly absorb about 90% of the incident spectrum, using the absorption coefficient of $2 \times 10^4\,cm^{-1}$ at 800 nm, is approximately 1 μm. Therefore, solar cells with such thin CdTe films (< 1 μm) has been of interest to achieve higher performance [2]. Optical confinement at the front contact in such thin (< 1 μm) CdTe films is one of the provisions to obtain higher efficiencies. We, therefore, introduced textured TCOs with different haze ratios to generate much more carriers from the increased path of incident light as well as by inhibiting the optical transmission loss in case of such 1-μm-thick CdTe absorption layers. As the most common approach to increase the photocurrent [3] of CdTe cells has been to reduce the CdS thickness, we also tried to optimize the CdS thickness in case of all TCOs.

2. Experimental

The transparent conducting oxides of ITO (indium tin oxide, sheet resistivity 8–12 Ω/cm^2) on Corning 1737 glass and textured TCO (SnO_2:F, sheet resistivity 4–15 Ω/cm^2) on a non-alkaline glass with different haze ratios were used for CdTe solar cells. Haze ratio expresses the transmittance ratio (in percentage) of scattered light to total incident light in case of TCO on glass. The thickness of CdTe absorber was varied from 0.5 to 3 μm to figure out the effect of optical confinement. Cadmium sulfide was deposited by the MOCVD technique. The thickness of CdTe layer was reduced down to 1 μm by controlling the temperature profile used during the CSS process. The temperatures of both the substrate and the source were raised together to 625°C and 1-μm-thick CdTe layer was achieved which showed strong preferential orientation in the (1 1 1) direction. Post-$CdCl_2$-treatment anneal and heat treatment after Cu-doped C attachment were carried out. Optimization in these different steps of cell fabrication process was carried out to drag out the best performance in case of such thin (1 μm) CdTe absorption layers. Moreover, the thickness of CdS was varied from 55 to 135 nm for each type of TCO to find out the optimum thickness of this window layer. The TCO films and CdTe cells were characterized using transmission, *I–V*, spectral response (SR), and atomic force microscopy (AFM) measurements.

3. Results and discussion

The structural properties of the TCOs were first studied using AFM. The grain size and roughness vary for these films as shown in Fig. 1. Larger grain size and roughness were obtained in the case of SnO_2:F with higher haze ratio. As can be seen from Fig. 1, the average roughness of A-TCO (haze 37%, 2000-nm-thick) is over 300 nm, whereas around 200 nm for B-TCO (haze 11%, 1000-nm-thick) and over 100 nm for C-TCO (haze 3%, 500-nm-thick) can be observed. ITO (250-nm-thick) is found to be smoother in roughness of around 10 nm and smaller grains than all the SnO_2:F films. The transmission spectra of the CdTe films (0.6-μm-thick) with different TCOs is

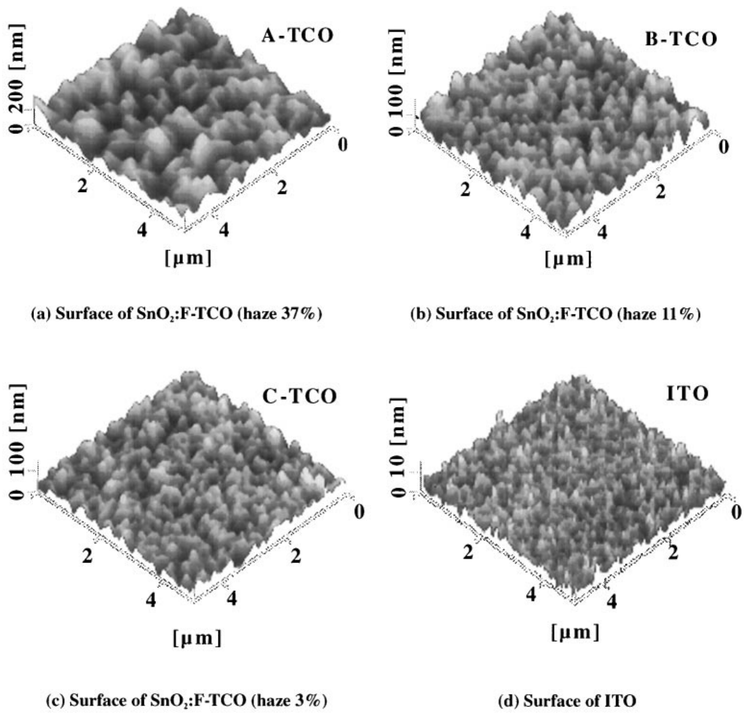

Fig. 1. AFM images of the surfaces of (a) SnO_2:F-TCO (37% haze ratio), (b) SnO_2:F-TCO (11% haze ratio), (c) SnO_2:F-TCO (3% haze ratio) and (d) ITO.

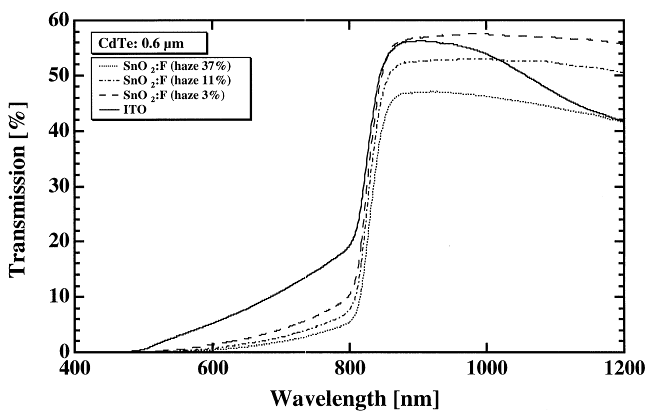

Fig. 2. Transmission spectra of the CdTe (0.6 μm) layers on different TCOs.

shown in Fig. 2, as an example of the optical confinement effect. The apparent decrease of the optical transmission in the range of 500–800 nm is due to the increased light scattering as the roughness of the SnO_2:F films increased. The values of optical transmission loss remain below 5% in case of textured tin oxides. On the contrary, an

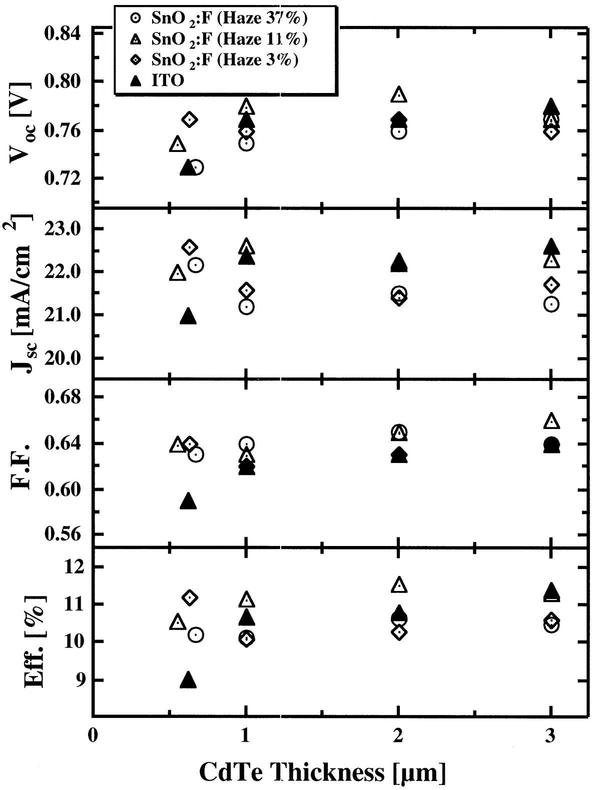

Fig. 3. Characteristics of CdTe solar cells with different CdTe thickness grown on different TCOs.

identical loss of about 10% in optical transmission occurs in case of the CdTe films with ITO.

The solar cell characteristics in respect to CdTe thickness of the cells fabricated using these specimens are shown in Fig. 3. All the cell performances deteriorate drastically in case of CdTe cell less than 1 μm thickness and ITO used as TCO. On the contrary, mostly J_{sc} highly contributes in overall cell performance in the case of textured tin oxide films even though the CdTe thickness is around 0.6 μm. J_{sc} values were over 22 mA/cm^2 and finally, 10–11% of efficiency was achieved in the case of textured SnO_2:F films and 0.6 μm-thick CdTe absorbers. All these results prove the effective optical confinement at the front contact in case of textured structure to a certain extent of haze ratio that results in higher absorption of the incident light, shown in Fig. 4, between the wavelength of 500 and 800 nm.

Furthermore, notable differences can be found among the textured TCOs with respect to the V_{oc}. Textured films with higher roughness show lower V_{oc}. It could be due to the non-uniform growth of CdS and CdTe, respectively, and that finally results in a weaker electric field throughout the absorber. The textured TCO with higher roughness (i.e., 37% haze) promotes the formation of alloying between CdS and CdTe

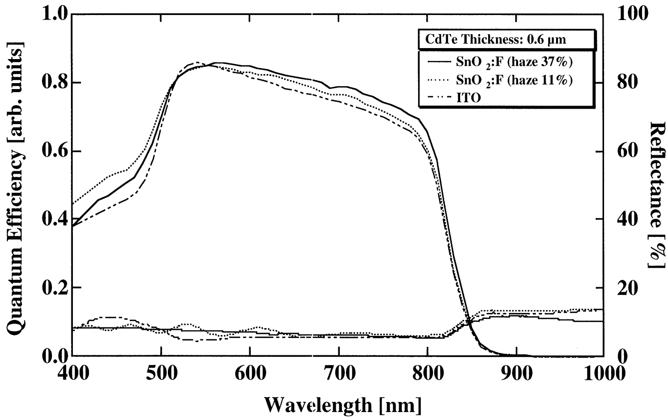

Fig. 4. Spectral response (SR) and reflectance of the CdTe cells with different textured TCOs.

as the initial CdS thickness was fixed at around 90 nm. The phenomena of the consumption of CdS window layer increasing as the roughness increases, as shown in other literature [4] supports the above assumption. Therefore, the optimization of CdS window layer is necessary to achieve higher collection efficiency and therefore to obtain higher conversion efficiency. The optimization of CdS thickness will be discussed later in this paper. Meanwhile, if the CdTe thickness is increased, the performances become different, as shown in Fig. 3. Cell performance of ITO increases as like as textured TCOs. The conversion efficiencies of 10.1% (V_{oc}: 0.75 V, J_{sc}: 21.2 mA/cm^2, FF: 0.64, area: 1 cm^2), 11.2% (V_{oc}: 0.78 V, J_{sc}: 22.6 mA/cm^2, FF: 0.63), 10.1% (V_{oc}: 0.76 V, J_{sc}: 21.6 mA/cm^2, FF: 0.62) and 10.7% (V_{oc}: 0.77 V, J_{sc}: 22.4 mA/cm^2, FF: 0.62) were achieved for the haze ratio of 37%, 11%, 3% and ITO, respectively, for 90-nm-thick CdS and 1-μm-thick CdTe absorption layer. Moreover, 2–3 μm of CdTe have been grown on these four types of TCOs. SnO_2:F-TCO with 11% haze ratio shows higher performance than all others with respect to the thickness from 0.5 to 2 μm of CdTe absorption layers.

In order to optimize the CdS window layer thickness, a series of solar cells were fabricated using TCOs with various roughness and by systematically varying the CdS thickness. In case of textured SnO_2:F-TCOs, the thickness of CdS was found to vary up to about 10 nm during MOCVD growth. This could be due to the fact that the nucleation depends on the surface properties of the SnO_2:F. It should also be noted that the final CdS thickness of these cells could vary considerably from the as-deposited value due to partial consumption of the CdS films during the cell fabrication process. The results obtained from these devices are shown in Fig. 5. The performances of the textured SnO_2:F with haze ratio of 11% and 3% show almost similar trend with respect to the CdS thickness, whereas the performance of SnO_2:F with 37% haze ratio shows deterioration below the CdS thickness of 80 nm. That suggests that CdS thickness should be thicker in case of rougher films to contribute in V_{oc} and J_{sc}, as assumed earlier. The range of 70–90 nm is found to be optimum in case

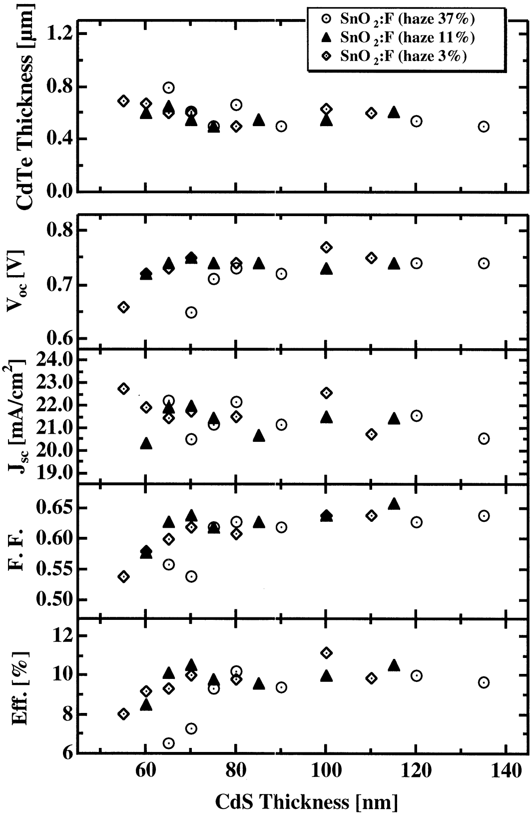

Fig. 5. The effect of CdS widow layer thickness in CdTe cells with different textured SnO_2:F-TCOs on solar cell characteristics.

of as-deposited CdS thickness with textured TCOs. Optimizing the CdS window layer thickness, 11.2% (V_{oc}: 0.77 V, J_{sc}: 22.61 mA/cm^2, FF: 0.64) was achieved for 100-nm-thick CdS layer with SnO_2:F-TCO of 3% and 0.6-μm-thick CdTe layer for all textured TCOs. Therefore, TCO's film roughness to a certain extent (e.g., 3% haze ratio) proved to have contribution in optical confinement and thus in overall performance even in case of the minimum thickness of CdTe absorber.

4. Conclusions

Textured TCOs of various roughness and grain sizes have been investigated to attain higher efficiency through confining the incident irradiation effectively for less than 1-μm-thick CdTe absorption layers. Noteworthy efficiencies were found in case of textured TCOs, such as 11.2% (V_{oc}: 0.77 V, J_{sc}: 22.61 mA/cm^2, FF: 0.64) was achieved for 100-nm-thick CdS layer with SnO_2:F-TCO of 3% haze ratio and

0.6-μm-thick CdTe layer. These results indicate useful hints to consider the insertion of textured TCOs as the front electrode in case of such (1 μm) thin CdTe solar cells to reduce the transmission loss as well as to confine the incident light and thus contribute to the higher efficiency.

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