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RESEARCH ARTICLE

The Effect of Surface Roughness of Substrates on the Performance of Polycrystalline Cadmium Sulfide/Cadmium Telluride Solar Cells

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The cadmium sulfide (CdS)/cadmium telluride (CdTe) heterojunction is a promising material combination for the development of cost efficient solar cells to meet the world's future energy demand. This study examined the effects of the surface roughness of six different layers, such as FTO, SnO_2 buffered FTO, thick and thin CdS layers deposited on these buffered and unbuffered FTO, on the photovoltaic performance of the corresponding CdS/CdTe solar cells. The morphologies of these surfaces were examined by atomic force microscopy (AFM). The short circuit current densities and fill factors of the devices were improved significantly when the SnO_2 buffer layer was introduced between the FTO and CdS layer. AFM images showed that surface roughness of the FTO coated glass substrates decreased when a buffer layer was present on FTO. The short circuit current densities and hence the external quantum efficiencies were improved further when the thickness of the CdS layer was reduced. This was attributed to the reduced filtering effect of the CdS layer. The optimized device showed an external quantum efficiency of more than 85% at the maximum absorption wavelengths of CdTe and an overall power conversion efficiency of more than 14.5% under an air mass (AM) 1.5 irradiation (100 mW cm^{-2}, 1 sun).

Keywords: CdTe Solar Cells, Surface Roughness, Buffer Layer, External Quantum Efficiency.

1. INTRODUCTION

Cadmium telluride (CdTe) has attracted considerable interest among several candidates for thin-film solar cell with significant ability to convert light into electricity.[1–3] CdTe solar cells have a favorable fabrication cost, processing methods and stability.[4] Solar cells produced using CdTe have reached adequate technological maturity to be one of the most successful photovoltaic technologies in the market.[5,6] The latest world record efficiency for cadmium-telluride (CdTe) photovoltaic (PV) module was 17.0% in May 2014 and the research cell efficiency of 21% was achieved by First Solar, Inc. in August 2014.[7,8] The fabrication of flexible and light weight CdS/CdTe solar cells has also attracted considerable interest for very high specific power and flexibility for curved shaping or rolling in terrestrial and space applications.[9–12]

CdTe is a group II^B–VI^A compound semiconductor with a direct optical band gap that is almost optimally matched to the solar spectrum for photovoltaic energy conversion. The high quantum yield can be expected over a wide wavelength range because of the direct band gap (E_g = 1.5 eV) and high absorption coefficient ($>5\times10^5$/cm) of CdTe.[13–15]

In conventional CdTe cells, polycrystalline cadmium sulfide (CdS) is used as the best suited *n*-type heterojunction partner over the last few decades.[16] CdS has been used as a window layer in solar cells owing to its wide band gap (2.42 eV).[17] The majority of studies of CdS/CdTe solar cells have been conducted in the superstrate configuration because all CdTe modules currently in commercial production were constructed in this configuration.[18] In the superstrate configuration, light enters the junction through a transparent substrate, typically soda lime glass. One of advantages of the superstrate design is that the

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surface of the CdTe is accessed easily for the formation of a back contact. The substrate-structured devices have also attracted interest as possible solar cells in flexible materials, such as high temperature polymers and ceramics.[19] Figures 1(a) and (b) present a schematic diagram of the superstrate and substrate device structures, respectively. The superstrate structure has a fluorine doped tin oxide (FTO) layer as the front contact and copper (Cu) followed by a gold (Au) layer as the top contact.

In superstrate structured devices, the formation of CdTe occurs after the growth of CdS thin films during the fabrication process. At high temperatures, the formation of $CdTe_{1-x}S_x$ is observed at the CdS–CdTe interface, and it was reported that the formation of $CdTe_{1-x}S_x$ ternary decreases the cell efficiency.[20,21] The formation of a $CdTe_{1-x}S_x$ ternary compound is due to the inter diffusion of CdTe into the CdS layer.[22] The interdiffusion depends on the nature and surface roughness of the CdS window layer and the residual oxygen present in the CdS surface prior to CdTe deposition. The CdS–CdTe interface was also reported to have a significant impact on the device performance.[23]

This study examined the correlation between the surface smoothness of the CdS window layer and the conversion efficiencies of the cells. The surface of the CdS film grown by chemical bath deposition (CBD) over bare fluorine-doped tin oxide (FTO) and undoped tin oxide (SnO_2) coated FTO glasses were characterized by atomic force microscopy (AFM).

2. EXPERIMENTAL PROCEDURES

Pilkington TEC 15 FTO glass was used for solar cell fabrication and SnO_2 buffer layers were deposited by chemical vapor deposition at the National Renewable Energy Laboratory (NREL), USA, as outlined in Ref. [24].[24] CdS thin films were grown by chemical bath deposition (CBD) on cleaned FTO and SnO_2 coated FTO substrates, where as polycrystalline CdTe films were deposited by close spaced sublimation (CSS) on the CdS layer, as described in Ref. [25].[25] The active layers were annealed in $CdCl_2$ vapor by CSS to improve the crystallinity and grain size of CdTe.[26] All samples were etched in a nitric acid-phosphoric acid (NP) solution to remove the surface oxides and create a tellurium-rich CdTe surface after the $CdCl_2$ treatment. Copper and gold layers were deposited using an electron beam physical vapor deposition under a good vacuum (10^{-6} torr). To improve the ohmic contact, the samples were then annealed in flowing nitrogen to promote Cu diffusion and facilitate the formation of Cu_xTe.[27]

In each substrate ($1.5'' \times 1.5''$), sixteen devices were fabricated. Two thicknesses of CdS (referred as thick and thin CdS layers) on the SnO_2 buffered and bare FTO glass substrates were used, keeping the thickness of the active CdTe layer constant. The surface roughness of the bare and buffered FTO glasses, and the samples with the thick and thin CdS layers deposited on buffered and unbuffered FTO glass were measured by AFM. The absorption spectra were measured by ultraviolet-visible-near infrared (UV-VIS-NIR) spectroscopy. The photovoltaic performance of the fabricated solar cells was measured under illumination of 1 sun (air mass 1.5), and the external quantum efficiency (EQE) measurements were taken using a computer interfaced source measure unit (Keithley 2400) and a monochromator.

3. RESULTS AND DISCUSSION

Figure 2 shows the photovoltaic performance of the four different types of solar cells fabricated and characterized in this study. Figures 2(a) and (b) clearly show that the presence of a buffer layer improves the power conversion efficiency and short circuit current density (J_{sc}), particularly in a device with a thin window layer, but there were no significant changes in the open circuit voltage (V_{oc}) (Fig. 2(c)) of the thick window layer cells. In contrast,

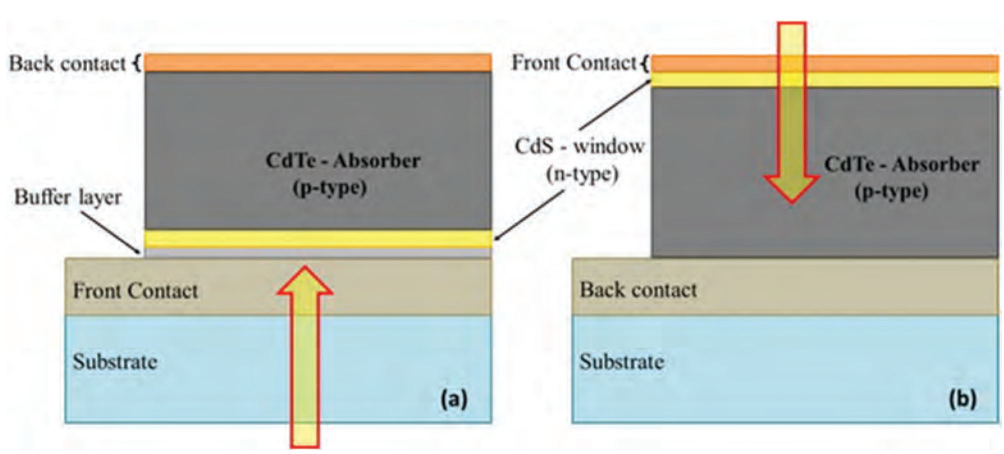

Fig. 1. Schematic diagram of a cross-section of a CdTe solar cell in (a) superstrate, and (b) substrate configuration, where the arrows show the direction of illumination.

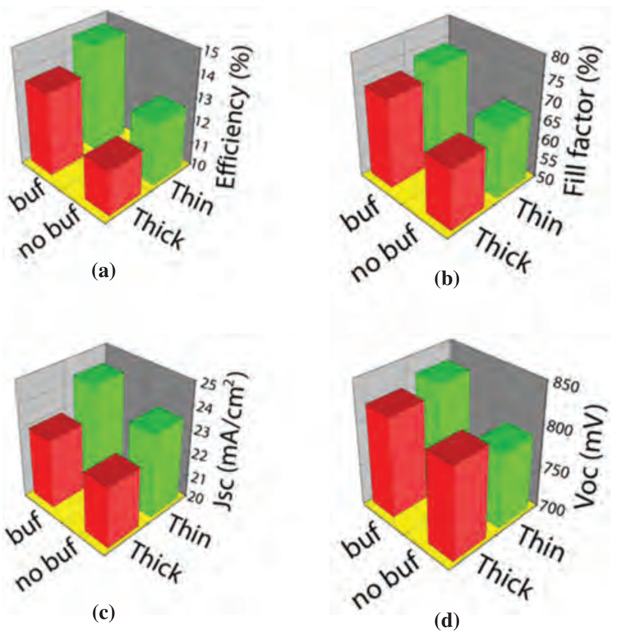

Fig. 2. Variation of (a) conversion efficiency, (b) short circuit current density J_{SC}, (c) open circuit voltage V_{OC}, and (d) fill factor of the cells with thick and thin window layer on buffered and bare FTO glass substrates.

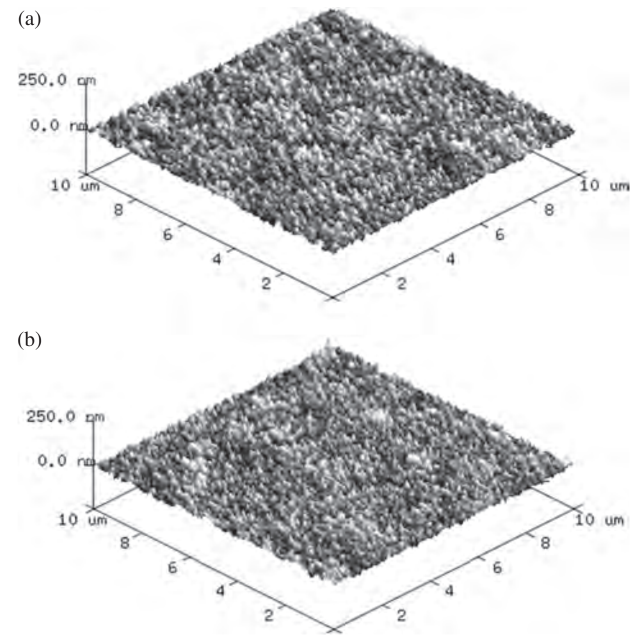

Fig. 4. AFM images of the surfaces of (a) bare FTO (b) SnO_2 buffered FTO substrates.

a significant change in V_{oc} of the cells with a thin window layer was observed due to the dominance of CdS, which was reported earlier.[24] Figure 2(d) clearly shows the improvement of fill factor due to the presence of the buffer layer. Figure 3 shows the absorption spectra of the 50 nm and 80 nm thick CdS window layers over the visible spectrum and the respective EQE spectra of the fabricated FTO/CdS/CdTe/Cu/Au devices with those window layers. The EQE curve presents the decrease in J_{sc} due to the strong absorption by the thick CdS layer below 500 nm. Even the absorption of CdS was low in the near infrared region; the EQE decreased due to the increased scattering.

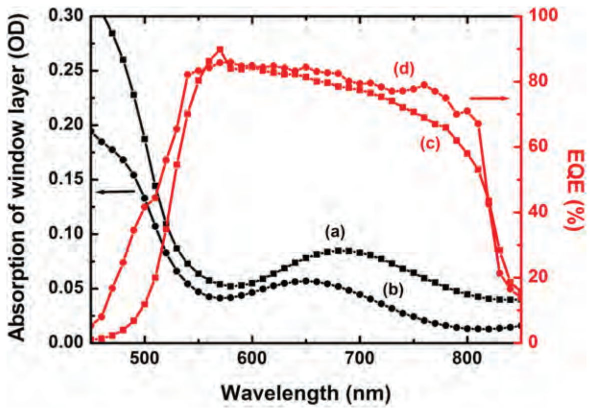

Fig. 3. Absorption of (a) thick CdS, (b) thin CdS layers deposited on FTO glass and the external quantum efficiencies of the devices with (c) thick CdS, (d) thin CdS.

Increased structural defects in the thick CdS layer might be the reason for the scattering in the near infrared region.[28]

Figures 4(a) and (b) present the topology of the surfaces of the bare FTO and SnO_2 coated FTO layer, and Figures 5(a)–(d) show the AFM images of the surfaces of thin and thick CdS layer deposited on FTO and buffered FTO. Table I lists the corresponding RMS roughness of the measured surfaces.

According to Table I, the RMS roughness of the FTO surface was higher than that of the buffered FTO surface. The surface of the thin CdS layer deposited on buffered FTO glass was smoother than the layer deposited on bare FTO glass. This shows that the surface roughness of samples with thin CdS is influenced by roughness of the substrate. On the other hand, the roughness of the thick CdS layer was unaffected by the substrate surface roughness because it was determined by the thicker CdS.

For thin CdS layer devices, pinholes and localized contacts between FTO and CdTe can form during high temperature deposition of the CdTe layer that reduce the shunt resistance of the device. This situation is prevented by the presence of a SnO_2 buffer layer, which gives a higher J_{sc} and fill factor than the device without the buffer layer.

Figure 6 presents the current density–voltage (J–V) characteristics of the optimized device under air mass (AM) 1.5 irradiation (100 mW cm^{-2}, 1 sun). This device showed the external quantum efficiency over 85% at the maximum absorption wavelengths of CdTe and an overall power conversion efficiency of more than 14.5% under air mass (AM) 1.5 irradiation (100 mW cm^{-2}, 1 sun).

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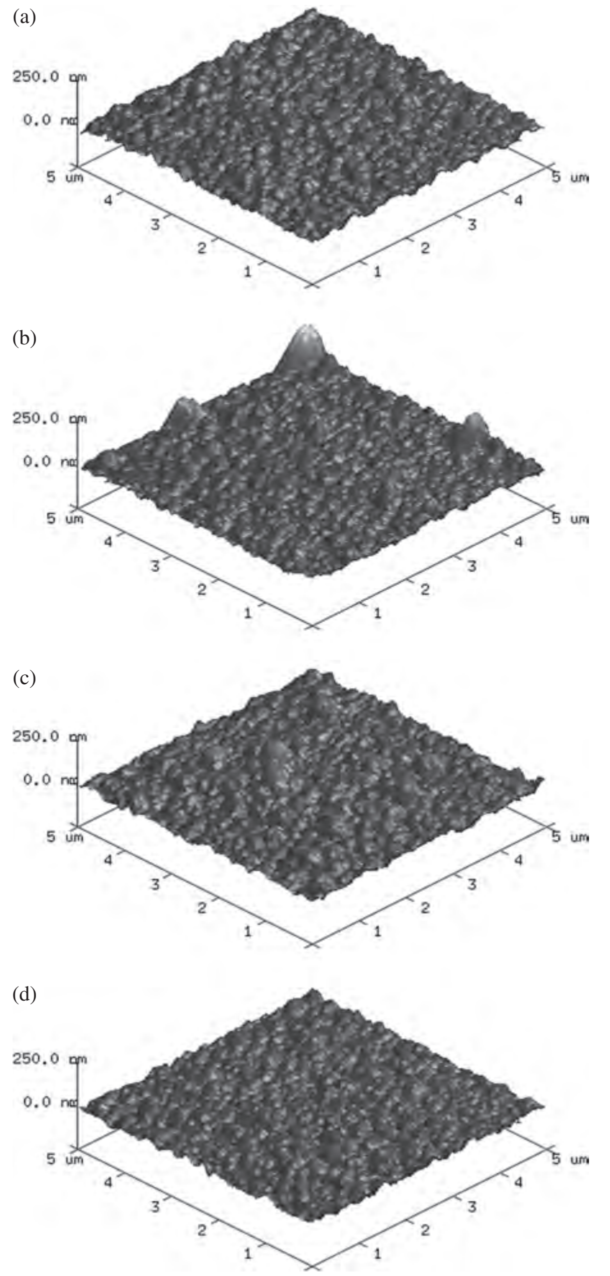

Fig. 5. AFM images of the surfaces of (a) thin CdS layer on FTO (b) thin CdS layer on buffered FTO (c) thick CdS layer on FTO (d) thick CdS layer on buffered FTO.

Table I. Variation of the RMS roughness of the bare FTO, FTO/sputtered SnO_2 buffer layer glasses, thick and thin CdS layer deposited on buffered and unbuffered FTO-coated glass substrates.

Surface	RMS roughness (nm)
Bare FTO coated glass	10.7
SnO_2 buffer coated FTO glass	9.85
Thin CdS layer on FTO glass	14.4
Thin CdS layer on buffered FTO glass	13.6
Thick CdS layer on FTO glass	18.7
Thick CdS layer on buffered FTO glass	18.5

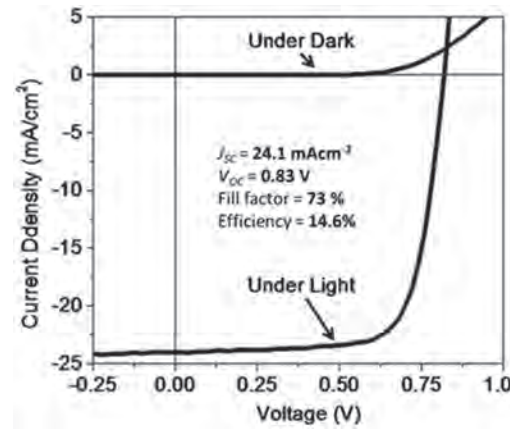

Fig. 6. *J–V* characteristic curves of the optimized device with thin CdS layer grown in SnO_2 buffered FTO glass in dark and under 100 mW/cm^2, AM 1.5 illumination.

4. CONCLUSIONS

The overall performance of the CdS/CdTe solar cells was optimized in cells with a buffer layer and a thinner CdS window layer. The surface roughness of the FTO coated glass substrates was reduced by the presence of a buffer layer on the top of FTO and the roughness of the thin CdS layer also depends on the substrate roughness, which improves the V_{oc} of the device with the thin window layer significantly by avoiding the formation of localized active layer FTO junctions in the cell. The structure with a thinner window layer had a better spectral response than those of the structure with a thick window layer, which can be improved further by smoothing the FTO bottom layer. The application of a buffer layer also makes the FTO layer smoother and avoids the formation of pinholes in the thin window layer, which results in the best device with an energy conversion efficiency approaching 15%.

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