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Enhancement of the photocurrent and efficiency of CdTe solar cells suppressing the front contact reflection using a highly-resistive ZnO buffer layer


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ABSTRACT

We report on the effects of using an atomic layer deposited ZnO transparent buffer layer with > 10^6 Ω cm resistivity on the performance of CdZnS/CdTe solar cells grown by metalorganic chemical vapour deposition (MOCVD). The buffer film thickness is adjusted by optical modelling to suppress the reflection losses at the front contact. A clear improvement, up to 1.8% in conversion efficiency, was obtained in comparison to reference devices without the ZnO buffer layer, thanks to the enhancement of the current density (J_sc) and fill factor (FF). Device spectral response showed improved collection for most of the visible region. Reflectance measurements confirmed that the ZnO film reduced the optical reflectance around the transparent front contact. This effect permitted light management through the front contact leading to an improvement of the J_sc and hence the photovoltaic conversion efficiency. These results are intriguing since the literature on CdTe solar cells did not previously report improvement to the photocurrent and device response through controlling the highly-resistive transparent buffer layer.

1. Introduction

The interest in cadmium telluride (CdTe) thin film solar cells from both academia and industry has risen significantly due to the recent record device efficiencies of 22.1% for cells and 18.6% for modules [1]. CdTe solar cells produced by metalorganic chemical vapour deposition (MOCVD) has also gone through significant improvements in recent years. High performance cells and mini-modules were reported without the ZnO buffer layer, thanks to the enhancement of the current density (J_sc) and fill factor (FF). These results were attributed to improved collection and open circuit potential (V_oc) parameters with the inclusion of the HRT layer at the front contact. Spectrally-resolved FF measurements indicated enhanced carrier collection in the long wavelength (500–800 nm) region, which was interpreted to emanate from strengthening of the collection field as well as carrier lifetime in the absorber layer. Fedorenko et al. studied ~ 100 nm thick ZnO, ZnSe, and ZnS films as the HRT layer for CdS/CdTe devices [7]. Device efficiency was found to be much poorer when using ZnSe or ZnS HRT films while no specific performance gain was observable for the ZnO HRT case. These results were attributed to inefficient doping and formation of recombination centers within the CdTe absorber, in relation to the extreme thinning of the window layer often leads to poor substrate coverage and hence localized TCO-absorber direct junctions which produces a poor junction [5]. However, contradictory results were obtained as to how much the performance and which device parameters are actually improved with the use of a HRT buffer film. Ferekides et al. studied the performance of CdTe solar cells for which a variety of TCO (indium-tin-oxide (ITO), SnO2:F, and CdIn2O4) and HRT (SnO2, In2O3, and ZnSnO4) layer combinations were used [6]. In general, they reported performance boost via the shunt resistance (R_sh) and open circuit potential (V_oc) parameters with the inclusion of the HRT layer at the front contact. Spectrally-resolved FF measurements indicated enhanced carrier collection in the long wavelength (500–800 nm) region, which was interpreted to emanate from strengthening of the collection field as well as carrier lifetime in the absorber layer. Fedorenko et al. studied ~ 100 nm thick ZnO, ZnSe, and ZnS films as the HRT layer for CdS/CdTe devices [7]. Device efficiency was found to be much poorer when using ZnSe or ZnS HRT films while no specific performance gain was observable for the ZnO HRT case. These results were attributed to inefficient doping and formation of recombination centers within the CdTe absorber, in relation to the extreme thinning of the window layer often leads to poor substrate coverage and hence localized TCO-absorber direct junctions which produces a poor junction [5]. 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These results were attributed to inefficient doping and formation of recombination centers within the CdTe absorber, in relation to the
effect of strain on the electronic properties of the grain boundary interface states. Williams et al. reported the effect of ZnO HRT films grown by atomic-layer-deposition (ALD) and sputtering on Cu(In,Ga)Se (CIGS) solar cells employing a CdS window layer [8]. Some ZnO films were treated with an oxygen plasma to increase their electrical resistance. It is found that cells with lower resistivity (as-deposited) HRT performed better than those with a high resistivity (plasma-treated) HRT ZnO film.

More recently, through optical modelling Womack et al. showed the possibility of an anti-reflection (AR) behaviour, observable when using a ZnO or SnO₂ buffer layer in CdS/CdTe solar cells [9]. The reflection and transmittance in TCO/HRT/CdS/CdTe stacked thin film device structures were calculated using the transfer matrix method, as function of the HRT and CdS window layer thickness. It was found that due to the low absorption in the ZnO layer it was possible to achieve window/ ZnO layer combinations that provide useful broad anti-reflection effects.

In this study we focus on ZnO thin film material deposited by ALD to study its contribution to CdTe solar cells as a HRT buffer layer which could possibly impart an AR property to the transparent front contact. The choice of ALD emanates from its proven ability to provide uniform, pin-hole free and conformal coatings at relatively low growth temperatures [10–12], which is essential for good coverage of the rough TCO layer without degrading its electrical conductivity. Optical modelling was used to aid the experimental work to suppress the reflection in the front contact region and thereby to boost the photocurrent. We observed a clear enhancement in the performance of all devices fabricated with the designed HRT layer due mainly to the optical gain and shunt resistance it provided. To our knowledge, this is the first experimental report which significantly improved the performance of a CdTe solar cell by reducing the reflection loss due to the front contact, using a suitable HRT buffer. Detailed device characterization and simulation results will be presented to explain the origins of the changes observed in device operation.

2. Experimental

Undoped ZnO buffer layers were deposited onto commercial 5.0 × 2.5 cm² boro-aluminosilicate glass coated with a 150–200 nm indium-tin-oxide (ITO) TCO layer (4–8 Ω/□ sheet resistance with 30 nm SiO₂ underlayer) as well as reference oxidized silicon substrates by ALD at 120 °C. ZnO film thickness was controlled to be in the region of 50 nm, which was predicted to effectively suppress the optical reflection around the ITO film. The Zn and O precursors used were diethylzinc and H₂O, respectively. The growth process followed was similar to that in Refs. [8,10], which provided good reproducibility and high electrical resistance. Four-point probe measurements carried out on ZnO films deposited on reference substrates showed an electrical resistivity on the order of 1–5 × 10⁶ Ω·cm. Ellipsometry was measured on reference ZnO films to obtain the refractive index (n, k). It is worth noting that no additional AR coating was applied to the glass/air interface.

Thin film Cd₁₋ₓZnₓS/CdTe:As solar cells were deposited using MOCVD in a horizontally configured growth chamber and H₂ carrier gas at atmospheric pressure. In every cell deposition run, one uncoated and one ZnO coated ITO substrates were placed side-by-side in the chamber, in order to have a direct comparison of the MOCVD film properties and the solar cell performance. Bare ITO substrates were surface-treated with an O₂ plasma prior to MOCVD which improves lateral uniformity. This treatment process was omitted for the ZnO/ITO substrates due to the strong influence of O₂ plasma on ZnO electrical resistance which tends to increase by several orders of magnitude [8]. Instead, ZnO/ITO substrates were kept sealed after the ALD process and only blown with dry N₂ gas before loading them into the MOCVD chamber. The thickness of Cd₁₋ₓZnₓS window layer (referred as CdZnS window hereafter) was varied between 60 and 150 nm with Zn concentration (x) set to 0.7. Extrinsic As doping was used to obtain CdTe with p-type conductivity, with concentration of ~ 3 × 10¹⁸ atoms/cm² for the bulk of CdTe absorber (2000 nm) and ~ 1 × 10¹⁷ atoms/cm² for the heavily-doped CdTe back contact layer (250 nm). The CdCl₂ heat treatment for cell activation was carried out after depositing CdCl₂ at 200 °C and annealing the samples under the H₂ ambient at 420 °C for 10 min. After cooling the substrates to room temperature and rinsing the excess CdCl₂ using deionised water, a post-deposition anneal was also performed in air ambient at 170 °C for 90 min for further cell activation. Further details on MOCVD growth of individual layers as well as device processing can be found in Refs. [3,13].

Solar cells of 0.5 × 0.5 cm² area were finished by masked-deposition of a ~ 200 nm gold (Au) film on each sample via thermal evaporation. The current density-voltage (J-V) curves were obtained employing an Abet Technologies Ltd. solar simulator in dark and light conditions. The intensity of the lamp output (AM1.5 solar spectrum) was calibrated using a GaAs reference cell. The device spectral response was characterized by measuring the external quantum efficiency (EQE) on a Bentham PV300 quantum efficiency system without a bias. The response of the system was corrected with respect to the output of a reference crystalline Si photodetector. The concentration and depth profiling of the arsenic dopant in the CdTe film were measured by secondary ion-mass spectroscopy (SIMS) using a Cameca IMS-4f instrument. The primary source was Cs⁺ ions operated at 10 keV energy with 20 nA current. The specimen to be analysed was cleaved (to ~ 1 × 1 cm² size) from the main sample and then etched in 0.2% bromine in methanol solution in order to reduce the surface roughness and thereby improve the depth resolution. An ion-implanted CdTe:As layer served as the calibration specimen.

3. Optical and device simulations

The reflectance data were modelled using The Essential Macleod, an optical modelling software based on the transfer matrix method [14]. The optical light is introduced through the glass substrate in normal direction. The optical constants (n, k) were taken from the table of materials with the software, except for the ZnO layer for which these were taken from ellipsometry data. Due to lack of available data, CdS was selected in place of the CdZnS material due to their material and functional similarity. Thickness of the films involved were kept close to their nominal values with some flexibility considered to account for the experimental variations due to deposition and post-processing. Table 1 provides the film thicknesses and the refractive indices (n, k at 510 nm) used in the optical model.

Device structures were modelled using SCAPS, a one-dimensional thin film solar cell simulation software [19] to investigate the effect of ZnO HRT layer on the performance of CdZnS/CdTe solar cells. Material parameters used in these simulations (mostly taken from previous work [3]) are given in Table 2. The carrier density of the CdTe and ZnO layers

<table>
<thead>
<tr>
<th>Source</th>
<th>Material</th>
<th>n</th>
<th>k</th>
<th>Thickness (nm)</th>
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</thead>
<tbody>
<tr>
<td>Medium</td>
<td>Glass</td>
<td>1.52083</td>
<td>0.00000</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>SiO₂</td>
<td>1.46180</td>
<td>0.00000</td>
<td>30</td>
</tr>
<tr>
<td>1</td>
<td>ITO</td>
<td>1.94000</td>
<td>0.01000</td>
<td>180</td>
</tr>
<tr>
<td>2</td>
<td>ZnO</td>
<td>2.06286</td>
<td>0.00018</td>
<td>0–50</td>
</tr>
<tr>
<td>3</td>
<td>CdS</td>
<td>2.50192</td>
<td>0.02695</td>
<td>110</td>
</tr>
<tr>
<td>4</td>
<td>CdTe</td>
<td>3.11402</td>
<td>0.49164</td>
<td>2000</td>
</tr>
<tr>
<td>Medium</td>
<td>Air</td>
<td>1.00000</td>
<td>0.00000</td>
<td></td>
</tr>
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</table>
as well as device parasitic resistances ($R_{sh}$, $R_s$) were taken directly from the experimental J-V data.

### 4. Results and discussion

Modelling showed that a ZnO film thickness in the region of 50 nm provided the highest AR effect for an ITO layer of ~180 nm thickness. The simulated reflection spectra with and without a ZnO buffer film of 50 nm in the ITO/HRT/CdS/CdTe device structure is given in Fig. 1. It is noticeable that the broad reflection peak at 625 nm observable for the non-HRT case is suppressed, along with some other gains obtained at other wavelengths, for the HRT device. This demonstrates that a 50 nm ZnO buffer layer can introduce AR to the ITO substrate used in our experiments.

The quantum efficiency (EQE) and J-V parameters of three pairs of devices, each with and without the HRT layer, and employing variable CdZnS thickness (60, 100, and 150 nm) are given in Fig. 2 and Table 3, respectively. The blue/near UV response is improved with thinner CdZnS in both cases, as can be expected from the improved transmission into the absorber. Meanwhile, the quantum efficiency of non-HRT cells shows greater variability and is inferior to that of HRT devices in the 500–850 nm range. As a result, the photocurrent is improved when using the HRT layer, albeit the absorption loss due to ZnO film (bandgap 3.37 eV), for each set of devices. Importantly, the device response was much more uniform for cells with the HRT layer. The mean short-circuit current density ($J_{sc}$) and fill factor ($FF$) are improved by $\sim 2$ mA cm$^{-2}$ and $\sim 4\%$, respectively, when the HRT layer is used. The $FF$ seems to benefit from an apparent rise in the shunt resistance ($R_{sh}$) as well as a small drop in series resistance ($R_s$). On the other hand, the open circuit potential ($V_{oc}$) for HRT devices with the 100 and 150 nm thick CdZnS is surprisingly lower (by ~20 mV) than their non-HRT counterparts, while for the 60 nm CdZnS layer the $V_{oc}$ is substantially higher with the HRT layer.

Fig. 3 presents the light J-V curve and the EQE spectrum of the best cells obtained for both substrate types when CdZnS is 100 nm thick. The efficiency increases from 13.1% for non-HRT cell to 14.8% for the HRT cell, whereby the $FF$ is improved by 2.3% and the $J_{sc}$ by 2.5 mA cm$^{-2}$ while the $V_{oc}$ reduced by 20 mV. The $J_{sc}$ increase (by 11.5% relative) with the HRT layer is particularly significant and comes mainly from the improved collection in the 500–900 nm region, which deserves a detailed explanation.

Let’s first examine the improvement to the $J_{sc}$ and spectral response when using the ZnO HRT layer. Enhancement of the quantum efficiency at most wavelengths (as seen in Fig. 2b) indicates improved light capture and/or carrier transport by the absorber. These could be possible by the virtue of (1) the front contact/window layer stack becoming more transparent, and (2) the electronic quality of the absorber.
As predicted from optical simulations, increased transmittance is likely to result from reduced reflectance losses around the front contact. To verify the AR effect, reflectance of two devices grown simultaneously, with and without the 50 nm ZnO HRT layer, were measured (Fig. 4a). Compared to the model data (Fig. 1), suppression of the reflectance at most visible wavelengths is evident for the HRT device which demonstrates that the ZnO layer indeed introduced AR to the ITO substrate. In Fig. 4b, the change in the quantum efficiency is compared to that of the reflectance for the same devices. Between 400 and 700 nm the spectra are in close agreement, indicating that device spectral response and the Jsc benefit strongly from the AR property in this region. Above 700 nm EQE of the HRT device is markedly superior to that of the non-HRT device, beyond the prediction of the reflectance gain. The additional gain in EQE may result from a change in the electronic properties of the semiconductor films due to a change in the growth substrate, i.e. ITO vs. ZnO/ITO. A small change in the MOCVD kinetics (e.g. due to the deposition substrate) can influence the film composition and properties, especially in terms of dopant...
distribution and carrier density. Such a small difference is indeed observed in the As concentration and consequent p-type doping density in the CdTe absorber (see Fig. 1 in Ref. [20]). Slightly higher bulk recombination at long wavelengths for the non-HRT device may be linked with its higher As density, whereby mostly As atoms are compensated for due to the low dopant activation ratio (~ 1%). Finally, the loss of EQE between 300 and 370 nm is due to absorption by ZnO.

Next, let’s discuss the small Vocc loss encountered when using a HRT layer with ≥ 100 nm thick CdZnS window (Table 3). In the related literature, there is no loss, but usually a gain, of Vocc reported when using a ZnO HRT layer with CdTe solar cells [21,22]. For example, Mahabaduge et al. employed 1 × 10−6 Ω− cm resistivity ZnO films as the HRT layer for sputter-deposited CdS/CdTe solar cells and found that the HRT layer improved the Vocc when thinner (40 nm) CdS was used but there was no noticeable difference for thicker (90 nm) CdS window layers [22]. This was attributed to blockade effect of the HRT layer on the shunt paths which are more prevalent for thinner window layers. Here, the small loss of Vocc, encountered even for 150 nm thick window layer, is likely to arise from (1) the energy band alignment at the material interfaces with the ZnO film incorporated into the device structure [8] or (2) the electronic quality (carrier density and/or lifetime) of the absorber [6,23]. A change particularly in the conduction band offset (CBO) between the absorber/window layers for CdTe solar cells can alter the interfacial surface recombination and hence device parameters [24]. Using SCAPS, we modelled our thin film device structures to examine the band alignment at the absorber/window/front contact interfaces. Although, the insertion of HRT layer produced narrow spikes at the interfaces to CdZnS and ITO (see Fig. 2 in Ref. [20]) these do not seem to lead to a change in the Vocc for a constant absorber carrier density of 1 × 1020 cm−3 (Table 4). However, when the apparent CdTe carrier densities from the C-V data (see Fig. 1 in Ref. [20]) are used in device simulations the Vocc of the HRT device is observed to reduce by ~20 mV, which agrees well with the experimental data. Thus, it is sensible to suggest that the Vocc of HRT devices can also be optimized by adjusting the p-doping density via the As concentration.

Devices with the thinnest (60 nm) CdZnS window layer showed a significant decrease in the Vocc and FF (Table 1). This observation agrees with previous reports where Vocc and FF fall rapidly as the CdS window thickness in CdS/CdTe solar cells is reduced to below 100 nm [4,25,26]. This effect is usually attributed to insufficient substrate coverage by the window layer. Extra-thin regions, or pin-holes, in the window layer would result in weak diodes between CdTe and the TCO layer with an increase in shunting. The ZnO HRT layer is partially effective in eliminating the effect of such bad junctions on device parameters. In this study, the optimal CdZnS window thickness reduced from 150 nm to 100 nm when using the ZnO HRT layer which also helped to enhance the photocurrent. It is believed all J-V parameters can be optimized by further tuning of the TCO/HRT bi-layer parameters and absorber doping.

5. Conclusions

CdTe solar cells with and without a highly conformal intrinsic ZnO layer were studied. The superstrate CdZnS/CdTe solar cells were grown side-by-side on ITO/glass and ZnO/ITO/glass substrates by MOCVD, where the CdZnS thickness was varied between 60 and 150 nm. Thickness of the ZnO HRT film was adjusted to ~50 nm through optical modelling to suppress the reflection losses around the front contact. In experiments, the reflection was indeed reduced at most visible wavelengths on incorporating ZnO to the front contact, leading to significant boost of the photocurrent (up to 11.5% relative). Additionally, the shunt resistance and fill factor were superior for the HRT devices, which provided a conversion efficiency improvement up to 1.8%, despite no gain was obtained in the open circuit potential (for ≥ 100 nm CdZnS). When using a very thin (60 nm) CdZnS window both Vocc and FF suffered significantly due to inferior substrate coverage, leading to poor TCO/CdTe localized junctions, whilst the ZnO HRT was effective in their recovery. The Jsc gain through reduced recombination at the front contact for CdTe solar cells is a new experimental observation. Overall, these results show that higher improvements to CdTe solar cells would be possible by further engineering the TCO/HRT metal-oxide front contact.

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