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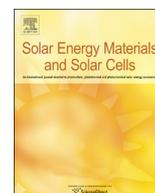
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Enhancement of the photocurrent and efficiency of CdTe solar cells suppressing the front contact reflection using a highly-resistive ZnO buffer layer



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ABSTRACT

We report on the effects of using an atomic layer deposited ZnO transparent buffer layer with $> 10^6 \Omega \text{ cm}$ 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 through window layer ($\text{Cd}_{1-x}\text{Zn}_x\text{S}$) optimization for higher photocurrents and a post-growth anneal for higher voltage and fill factors [2,3]. The MOCVD CdTe devices may be further improved via other approaches known to work for other chalcogenide thin film solar cells. One of these strategies is the use of a highly-resistive transparent (HRT) buffer layer, inserted between the transparent conducting oxide (TCO) electrode and the n -type window layers [4].

The use of a metal-oxide HRT buffer is commonly anticipated to allow further thinning of the window layer (to reduce its parasitic absorption) and thereby increase light transmission into the absorber and improve the photocurrent. In the absence of a HRT layer, considering the rough surface of the TCO on glass substrates normally used, 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), $\text{SnO}_2\text{:F}$, and CdIn_2O_4] and HRT (SnO_2 , In_2O_3 , and Zn_2SnO_4) layer combinations were used [6]. In general, they reported performance boost via the shunt resistance (R_{sh}), fill factor (FF) 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

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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

Doped ZnO buffer layers were deposited onto commercial $5.0 \times 2.5 \text{ cm}^2$ boro-aluminosilicate glass coated with a 150–200 nm indium-tin-oxide (ITO) TCO layer (4–8 Ω/\square 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 $1\text{--}5 \times 10^6 \Omega \text{ cm}$. 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 Cd_{1-x}Zn_xS/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 Cd_{1-x}Zn_xS 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 $\sim 3 \times 10^{18}$ atoms/cm³ for the bulk of CdTe absorber (2000 nm) and $\sim 1 \times 10^{19}$ atoms/cm³ 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 $0.5 \times 0.5 \text{ cm}^2$ area were finished by masked-deposition of a $\sim 200 \text{ nm}$ 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 $\sim 1 \times 1 \text{ cm}^2$ 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 library files available 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 1

Solar cell design and materials used to simulate reflectance data (incidence angle = 0 degrees; reference wavelength = 510 nm; n = refractive index; k = extinction coefficient). Sources for the optical constants were Refs. [15] (SiO₂), [16] (ITO), [17] (CdS), and [18] (CdTe).

Source: Sources for the optical constants were Refs.

Layer	Material	n	k	Thickness (nm)
Medium	Glass	1.52083	0.00000	
0	SiO ₂	1.46180	0.00000	30
1	ITO	1.94000	0.01000	180
2	ZnO	2.06286	0.00018	0–50
3	CdS	2.50192	0.02695	110
4	CdTe	3.11402	0.49164	2000
Medium	Air	1.00000	0.00000	

Table 2
Material parameters used in SCAPS device simulations.

Parameter	ITO	ZnO	CdZnS	CdTe:As	CdTe: As+
Thickness (nm)	200	50	150	2000	250
Bandgap (eV)	3.72	3.37	2.90	1.45	1.435
Electron affinity (eV)	4.50	4.00	4.26	4.28	4.28
Dielectric permittivity (relative)	9.4	9.0	9.3	9.4	9.4
CB density of states (cm^{-3})	4×10^{19}	1.8×10^{19}	2.1×10^{18}	1.5×10^{18}	8×10^{17}
VB density of states (cm^{-3})	1×10^{18}	2.4×10^{18}	1.7×10^{19}	1.8×10^{19}	1.8×10^{19}
Electron mobility (cm^2/Vs)	30	25	70	700	700
Hole mobility (cm^2/Vs)	5	25	20	60	60
Shallow donor density (cm^{-3})	1×10^{21}	1×10^{19}	1.2×10^{18}	–	–
Shallow acceptor density (cm^{-3})	–	–	–	1×10^{16}	2×10^{16}

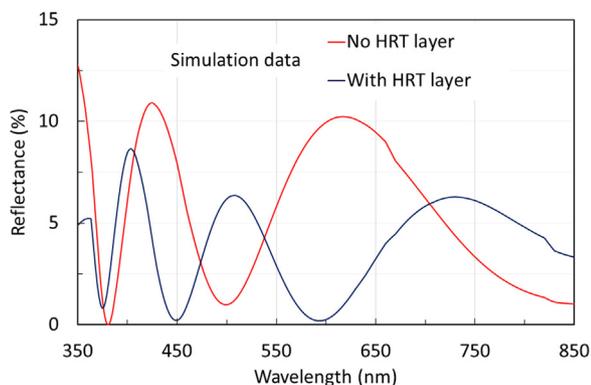


Fig. 1. Calculated reflection spectra of a CdTe solar cell structure with and without a 50 nm ZnO HRT layer. Reflection is suppressed at most visible wavelengths with the HRT film, suggesting more light will be transmitted to the absorber.

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 $\sim 2 \text{ mA cm}^{-2}$ 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. 3b) 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

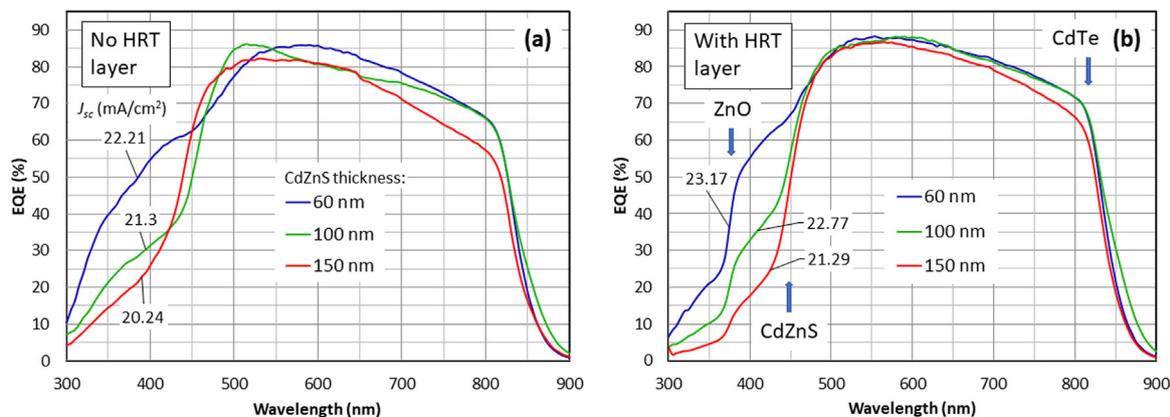


Fig. 2. EQE spectra of CdZnS/CdTe devices with different CdZnS thickness without (a) and with (b) the ZnO HRT layer. The J_{sc} values calculated via spectral integration are also given for each spectrum. Absorption edges due to ZnO, CdZnS, and CdTe are indicated in (b).

Table 3

8-cell mean J - V data of CdZnS/CdTe devices with different CdZnS thicknesses. HRT refers to the 50 nm ZnO buffer film between ITO front contact and CdZnS window.

HRT	CdZnS (nm)	V_{oc} (mV)	J_{sc} (mA cm^{-2})	FF (%)	η (%)	R_s (Ω)	R_{sh} (Ω)
No	60	432 \pm 37	23.4 \pm 0.9	60.2 \pm 2.3	6.1 \pm 0.8	3.5 \pm 0.3	642 \pm 130
Yes	60	641 \pm 21	24.9 \pm 0.5	64.0 \pm 3.1	10.2 \pm 0.7	3.5 \pm 0.2	1247 \pm 297
No	100	790 \pm 13	21.7 \pm 0.4	72.8 \pm 4.8	12.5 \pm 1.0	3.2 \pm 0.4	911 \pm 148
Yes	100	768 \pm 11	23.9 \pm 0.4	77.3 \pm 0.9	14.2 \pm 0.5	2.8 \pm 0.2	3077 \pm 596
No	150	798 \pm 11	21.9 \pm 0.6	75.9 \pm 2.3	13.3 \pm 0.7	3.5 \pm 0.2	1979 \pm 567
Yes	150	775 \pm 15	23.1 \pm 0.5	78.1 \pm 1.5	14.0 \pm 0.4	2.6 \pm 0.2	3127 \pm 751

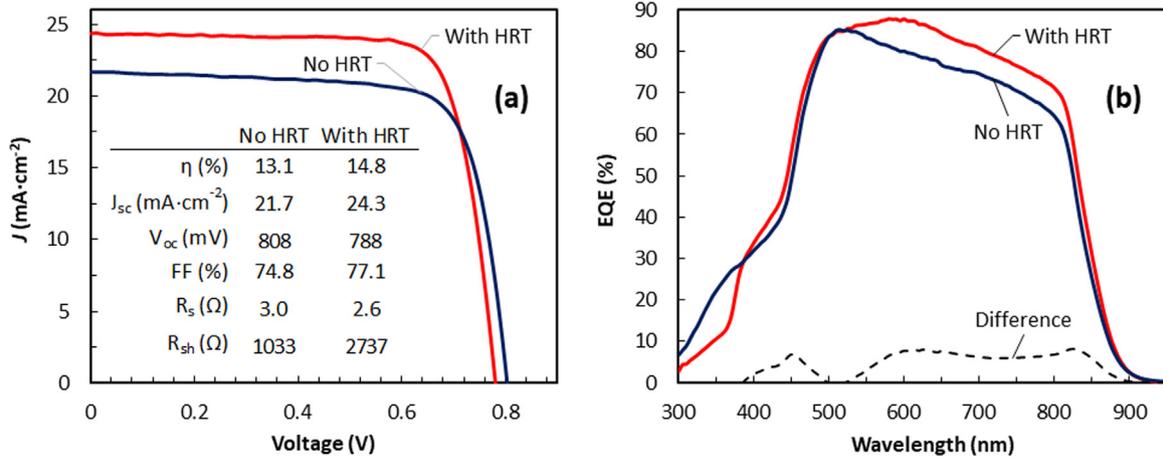


Fig. 3. The light J - V curve (a) and EQE spectrum (b) of the best cells found using 100 nm CdZnS, with and without the HRT layer. The extracted J - V parameters are given as inset to (a).

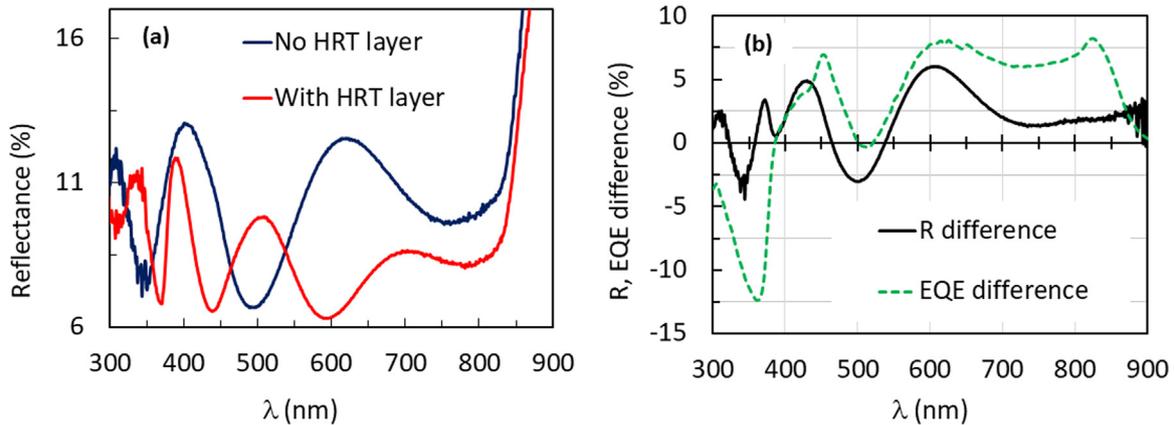


Fig. 4. (a) Reflectance spectrum of CdTe solar cells grown with and without the ZnO HRT layer, and (b) comparison of the change in reflectance and quantum efficiency for the same cells.

Table 4

Summary of the simulated J - V data for CdZnS/CdTe devices, with and without the 50 nm ZnO HRT buffer layer. Results for equivalent absorber carrier density ($N_a = 1 \times 10^{16} \text{ cm}^{-3}$) show no significant V_{oc} change between the two device structures, hinting that the V_{oc} is more sensitive to the absorber carrier density than the band alignment.

HRT	N_a (cm^{-3})	V_{oc} (mV)	J_{sc} (mA cm^{-2})	FF (%)	η (%)
No	1.7×10^{16}	857.20	25.00	73.79	15.24
No	1.0×10^{16}	834.60	24.24	73.15	14.80
Yes	1.0×10^{16}	835.30	24.10	75.46	15.19

increasing. 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 optical reflection for the same devices. Between 400 and 700 nm the spectra are in close agreement, indicating that device spectral response and the J_{sc} 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 most 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 V_{oc} 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 V_{oc} is reported when using a ZnO HRT layer with CdTe solar cells [21,22]. For example, Mahabaduge *et al.* employed $1 \times 10^5 \Omega\text{-cm}$ resistivity ZnO films as the HRT layer for sputter-deposited CdS/CdTe solar cells and found that the HRT layer improved the V_{oc} 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 V_{oc} 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 V_{oc} for a constant absorber carrier density of $1 \times 10^{16} \text{ cm}^{-3}$ (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 V_{oc} 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 V_{oc} 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 V_{oc} and FF (Table 1). This observation agrees with previous reports where V_{oc} 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 optimum 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 buffer 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 V_{oc} 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 J_{sc} gain through reduced reflectance 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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