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APPLICATIONS

# Electron reflector to enhance photovoltaic efficiency: application to thin-film CdTe solar cells

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## ABSTRACT

The incorporation of an electron reflector is a proposed strategy to improve the open-circuit voltage of CdTe solar cells. An electron reflector is a conduction-band barrier that can effectively reduce electron recombination at the back surface. In this work, the electron-reflector strategy is numerically applied to a thin-film CdTe record-cell baseline model (efficiency = 16.5%). Simulation shows that to have the optimal effect from an electron reflector, the CdTe thickness should be on the order of 1 μm, or slightly lower if the optical reflection at the back surface can be enhanced. Efficiency above 19% should be achievable with a 0.2-eV electron reflector and currently achievable parameters ($10^{14}$-$cm^{-3}$ hole density and 1-ns lifetime). Moreover, efficiency above 20% should be possible at a 1-μm absorber layer if large optical back reflection can also be achieved. 

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## 1. INTRODUCTION

The CdTe thin-film solar cell is one of the most promising photovoltaic devices from the standpoint of both cost and efficiency. The band gap of CdTe is near optimal for achieving high efficiency with the solar spectrum. In addition, CdTe's large optical absorption coefficient allows 2 μm of material to absorb more than 99% of incident light at 600 nm. CdTe solar cells can be fabricated with a variety of deposition techniques, because the electronic properties and the structure are generally optimized by post-deposition treatments. Economic fabrication processes have led to large-scale manufacturing [1,2], and the CdTe technology now accounts for over half of US photovoltaic production.

The record efficiency for a CdTe solar cell (16.5%) is, however, much less than its theoretical maximum efficiency (~29%), primarily because its open-circuit voltage (0.845 V) is well below that expected for its band gap (1.5 eV). In 2006, two strategies to increase the voltage of CdTe solar cells were proposed and briefly evaluated [3]. One strategy was to increase the CdTe carrier density and lifetime to values more comparable to single-crystal cells. The other was to add an electron reflector (ER) at the back contact of a fully depleted CdTe cell. The electron-reflector strategy is probably more practical for voltage improvement, because it does not require a major improvement in the quality of thin-film CdTe.

In a fully depleted CdTe cell, which has an electric field throughout the CdTe absorber, the field drives minority carrier electrons away from the back surface of the cell. Under forward bias, the built-in field is sufficiently reduced that it becomes less effective, and hence, more minority carrier electrons diffuse to the back surface, where there are many defect states and a high level of carrier recombination. Figure 1 shows the calculated band diagram of a fully depleted CdTe cell (a) without bias, (b) under forward bias *V*, and (c) with bias as well as an ER. Details such as the small CdS/CdTe conduction band offset are shown, and the implied small back-contact barrier for holes do not materially affect the results below. Note that with the low carrier density typical of thin-film CdTe, the CdTe layer will be substantially or fully depleted. The ER, which has a potential barrier of height $\varphi_e$ in the conduction band at the back surface of a solar cell, will reflect minority carrier electrons away from the back surface and thus reduce the back-surface recombination, especially under forward bias. The ER of a CdTe cell can be formed by adding a layer of p-type material with an expanded band gap and a negligible valence band offset on the back-contact side of the CdTe absorber. Alloys such as CdZnTe and CdMgTe should serve this purpose.

 

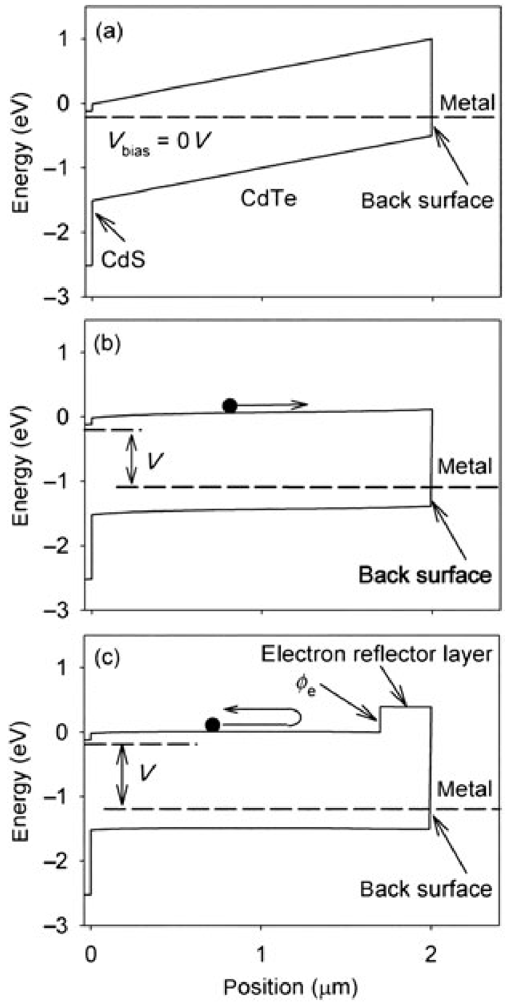


**Figure 1.** Calculated band diagram of a fully depleted CdTe cell (a) without bias, (b) under forward bias $V$, and (c) with bias as well as an electron reflector $\boldsymbol{\varphi}_e$.

In the section that follows, one-dimensional numerical simulation is used to apply the electron-reflector strategy to the CdTe record-cell baseline model to evaluate the potential effect on the efficiency of CdTe cells.

## 2. NUMERICAL SIMULATION

The software package AFORS-HET v2.2 (Helmholtz Zentrum Berlin, Berlin, Germany) [4] was used for the numerical simulations. This software allows the numerical solution of the coupled differential equations that describe the operation of a photovoltaic device. Output for the set of parameters specified includes the band diagram for the solar cell, the current density versus voltage (*J–V*) curve, and the carrier density and recombination rate profiles.

Previous baseline parameters for a CdTe thin-film solar cell [5] with minor adjustments to match the *J–V* curve of the record CdTe cell [6] were assigned to a four-layer device model [7]: CdS/bulk CdTe/ER/metal back-contact. The parameters used here have either been determined by independent measurements or are reasonable estimates. The minority-carrier lifetime of the absorber layer for the baseline setting is 1 ns, which has been achieved experimentally [8]. A 10-μm absorber layer, $10^{14}$-cm$^{-3}$ hole density, and a back-contact barrier corresponding to flat bands at the back surface were used for the CdTe record-cell baseline. The baseline hole density of $10^{14}$ cm$^{-3}$ is a typical value based on capacitance measurements from a variety of CdTe cells fabricated in different laboratories. Figure 2 shows that the calculated *J–V* curve of the record-cell baseline model used matches the experimental data for the record CdTe cell [6].

Figure 3 shows contour plots for calculated solar-cell parameters, including open-circuit voltage ($V_{oc}$), short-circuit current density ($J_{sc}$), fill factor ($FF$), and efficiency ($eff$), for variations from the CdTe record-cell baseline. Each plot shows absorber thickness on the $x$-axis and hole density on the $y$-axis. Variations in hole density, especially for the thinner range of absorber thickness, have only a minor impact on the *J–V* curves. Lifetimes less than 1 ns will yield smaller voltages and fill factors, but higher ones will not significantly improve efficiency unless carrier density is also increased [3]. In the contour plots, the black dots, which correspond to $d_{abs} = 10$ μm and $p = 10^{14}$ cm$^{-3}$, depict the values for the record-cell baseline, which are consistent with the solar-cell parameters of the record CdTe cell ($V_{oc} = 845$ mV, $J_{sc} = 25.9$ mA/cm$^2$, $FF = 75.5\%$, $eff = 16.5$ %) [6].

## 3. OPTICAL BACK REFLECTION

A metal contact such as gold or copper at the back surface of a solar cell should reflect much of the transmitted long-wavelength light back through the absorber layer. Long-wavelength, low-absorption light would therefore have a

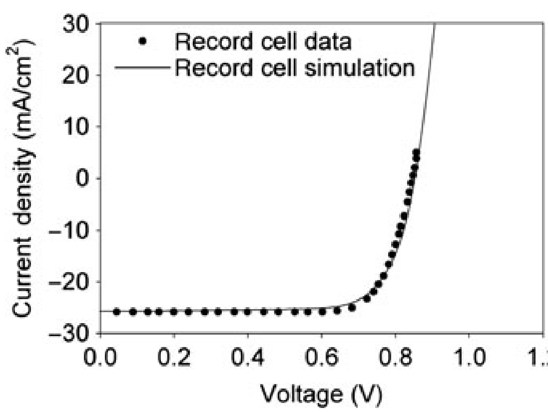


**Figure 2.** *J–V* curves of the record CdTe cell from reference [6] (dotted) and the baseline model used here (solid).


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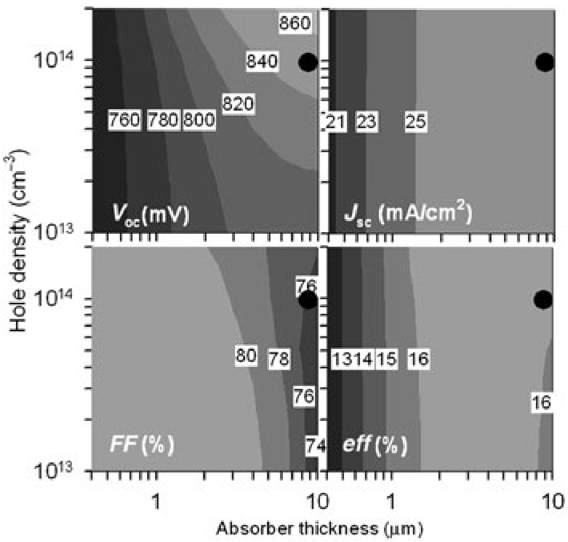


**Figure 3.** Carrier density/absorber thickness contour plots for calculated solar-cell parameters with $\varphi_e = 0\,\mathrm{eV}$ and $R_b = 0\%$. Black dots represent the CdTe record cell.

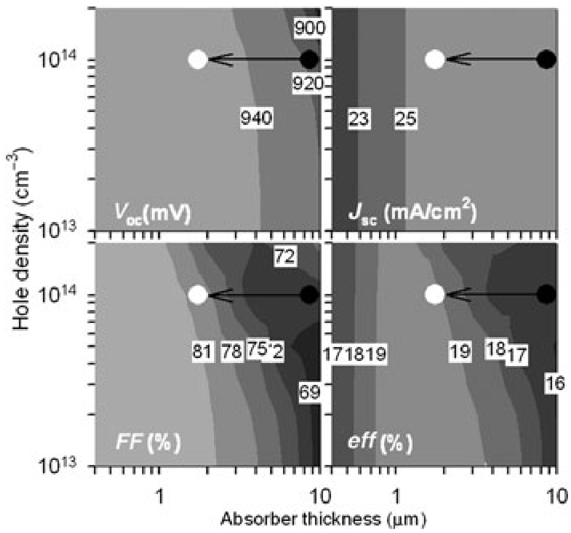


**Figure 5.** Carrier density/absorber thickness contour plots for calculated solar-cell parameters with $\varphi_e = 0.2\,\mathrm{eV}$ and $R_b = 20\%$. Black dots represent the record-cell thickness, and white dots represent a thinner cell maintaining the other record-cell parameters.

second pass through the CdTe, and the photon collection should be increased. The fraction of incident light reflected by the back surface is denoted by $R_b$. If $R_b = 100\%$, the effect on current density is the doubling of the optical absorption path. Figure 4 shows the calculated current density versus CdTe thickness and optical back reflection. At thicknesses below 2 μm, the higher optical back reflectivity begins to have a measurable effect on current density, and below 1 μm, the enhancement becomes very significant.

## 4. RESULTS

Figure 5, which is similar to Figure 3, shows the contour plots for the calculated solar-cell parameters of CdTe cells with $\varphi_e = 0.2\,\mathrm{eV}$ and $R_b = 20\%$. The black dots in the contour plots represent the record-cell baseline with $\varphi_e = 0.2\,\mathrm{eV}$ and $R_b = 20\%$. Figure 6 is similar with $R_b$ increased to 100%. In both cases for thicker absorbers, $V_{oc}$ is increased, and FF is decreased from Figure 3 with $\varphi_e = 0$, but the efficiency for the thick cell that is not fully depleted is essentially unchanged. $J_{sc}$ is not affected by $\varphi_e$ but is improved by optical back reflection (OR) with the absorber thickness below 2 μm. The benefit of electron and optical reflection is negligible for the 10-μm record-cell baseline because of its lack of full depletion and its already complete absorption.

To achieve the maximum improvement from an ER, the CdTe thickness should be on the order of 1 μm, or slightly lower if the OR can also be enhanced. White dots represent the thinned record-cell baseline with $\varphi_e = 0.2\,\mathrm{eV}$ and $R_b = 20\%$ in Figure 5, or $R_b = 100\%$ in Figure 6 (these values should span the physical range). Figure 5 shows a

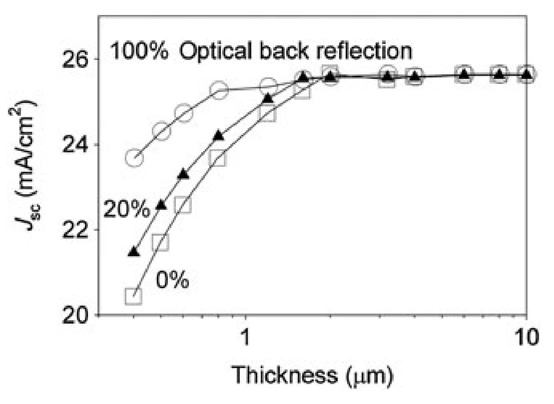


**Figure 4.** Calculated current density versus CdTe thickness for three values of optical reflection from the back surface.

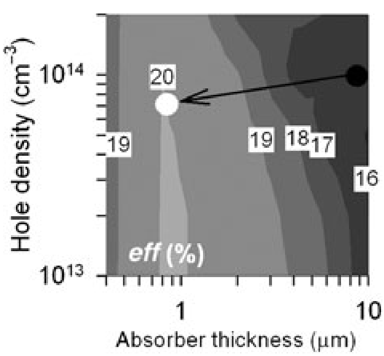


**Figure 6.** Carrier density/absorber thickness contour plots for calculated solar-cell efficiency with $\varphi_e = 0.2\,\mathrm{eV}$ and $R_b = 100\%$. The black dot represents the record cell thickness, and the white dot the thinned cell.


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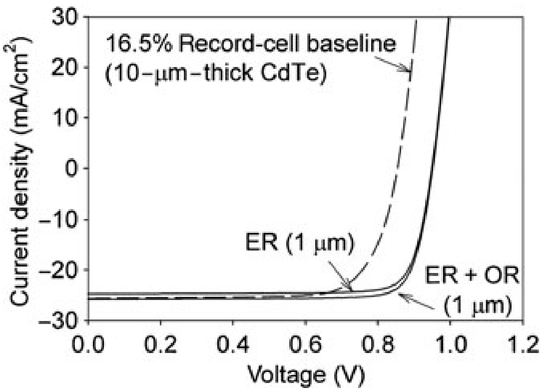


**Figure 7.** Calculated *J–V* curves for a 1-μm CdTe cell with a 0.2-eV electron reflector (ER) and 100% optical back reflection (ER + OR). The record experimental curve [6] (dashed) is shown for reference.

voltage increase of approximately 100 mV without loss of fill factor, corresponding to efficiency above 19%, which should be possible with an absorber thickness on the order of 1 μm. Moreover, Figure 6 shows that 20% efficiency should be achievable with $\varphi_e = 0.2$ eV, $R_b = 100\%$, and thickness slightly below 1 μm (white dot). Larger efficiencies would be possible if the CdTe lifetime could be increased above 1 ns.

Figure 7 shows the calculated *J–V* curves for a 1-μm CdTe cell with a 0.2-eV ER and the 100% OR (ER + OR). The record experimental curve is also shown for reference. With $\varphi_e = 0.2$ eV and a 1-μm absorber layer, $V_{oc}$ should be increased by 100 mV as shown in Figure 5, but the $J_{sc}$ will be reduced because of incomplete absorption. $R_b = 100\%$ can nearly completely compensate for the incomplete absorption loss. Based on the simulation, 20% efficiency should be possible with $\varphi_e = 0.2$ eV, $R_b = 100\%$, and a 1-μm absorber layer. If cell quality can be maintained, thinning cells to near 1 μm should be a practical way to benefit from electron and optical reflection.

## 5. CONCLUSIONS

In this work, one-dimensional numerical simulation was used to evaluate the potential effect of electron and optical reflection on CdTe solar cells. For the optimal effect from an ER, assuming no change in cell quality otherwise, the CdTe thickness should be on the order of 1 μm, or slightly lower if the optical reflection at the back surface can be enhanced. Based on the simulation, efficiency above 19% should be possible with a 0.2-eV ER and currently achievable parameters ($10^{14}$-cm$^{-3}$ hole density and 1-ns lifetime). Moreover, 20% efficiency should be possible if large OR is also achievable.

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