QUANTIFICATION OF LOSSES IN THIN-FILM CdS/CdTe SOLAR CELLS

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ABSTRACT

Quantification of solar cell losses can identify promising pathways for further cell improvements. This paper expands earlier work and applies it specifically to CdS/CdTe cells. For the analysis we have defined four cells: The Target cell is one that should be possible with current industrial processes. The Production cell is typical of today's production. The Record cell has the highest efficiency (16.5%) reported to date. The Ideal cell has the highest theoretical performance for CdTe. The systematic technique of separating losses, referred to as third level metrics, breaks current, voltage, and fill-factor losses down into their individual loss mechanisms. The losses are expressed both as the deficiency in the specific parameter and as the impact on cell efficiency. The latter allows clear identification of the most significant losses.

1. INRODUCTION

Thin-film CdS/CdTe devices have been studied extensively, but some basic underlying properties are not well understood, and progress towards higher cell performance has not been rapid. To identify the major problems in CdS/CdTe and other solar cells, we have long advocated quantitative separation of losses. This work expands earlier work [1,2] and applies it specifically to CdS/CdTe cells. The objectives are a) to present a systematic procedure to quantify individual losses in CdTe solar cells and b) to suggest strategies to achieve a 19% CdTe cell with modest reduction in forward current and realistic improvements in other selected parameters.

The loss analysis consists of four different cells: The Target, Production, Record and Ideal cells. The Target cell is a cell, which should be possible with current industrial processes, assuming the implementation of modest improvements. The Production cell is a typical production cell, and is used for illustration purposes, with the acknowledgement that many production cells have achieved higher performance. The Record cell with 16.5% efficiency has the highest efficiency credibly reported to date [3]. The Ideal cell is based on calculation of the highest theoretical performance. Quantitative separation of losses allows comparison among different cells. A systematic technique for separating losses is presented as First, Second, and Third level metrics. First-level metrics compare cell efficiency, both with other cells and with the theoretical maximum. Second-level metrics separate efficiency into current density (J_{sc}), voltage (V_{oc}) and fill-factor (FF). Third-level metrics break J_{sc}, V_{oc} and FF down into constituents that can be straightforwardly measured and have a clear physical interpretations.

2. FIRST AND SECOND LEVEL METRICS

First level metrics compare the efficiencies of the Production and Record cell with the Target cell (Table 1). R-P is the efficiency difference between the Record and Production cells, and T-R between Target and Record. The Production cell is 6.9% less efficient than the Record cell, and the Record cell is 2.5% less efficient than the Target cell, with the assumed parameters. The Ideal cell is 3.9% more efficient than the Target cell. Figure 1 compares the current voltage characteristics of these four cells.

Table 1. Efficiencies of designated cells.

	Prod.	Record	Target	R- P [Δη%]	T-R [Δη%]
Efficiency	9.6	16.5	19.0	6.9	2.5

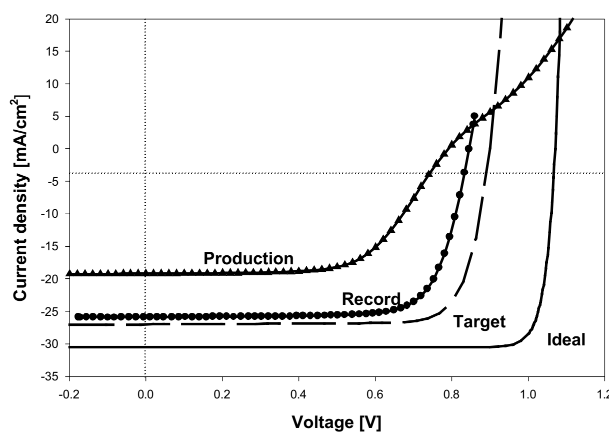

Figure 1. Current-Voltage characteristics of the four cells to be discussed.

Second-level metrics analyze efficiency in terms of the standard solar-cell parameters J_{sc}, V_{oc} and fill-factor. In Table 2 the individual cell parameters, as well as their impact on the cell performance, are shown. Of the Production cell's 6.9% lower efficiency compared to the Record cell, 3.6% is due to lower J_{sc}, 0.9% is due to lower V_{oc}, and 2.4% is due to smaller FF. A 19% Target cell can be achieved with modest improvements shown in Table 2. Ideal-cell parameters can be inferred from Figure 1.

Table 2. Second Level Metrics

	Prod.	Record	Target	R- P [Δη%]	T- R [Δη%]
V_{oc} [mV]	791	845	900	0.9	1.1
J_{sc} [mA/cm^2]	19.2	25.9	27.0	3.6	0.7
Fill-Factor	62.2	75.5	78.5	2.4	0.7
Efficiency	9.6	16.5	19.0	6.9	2.5

3. THIRD LEVEL METRICS

Here the second level metrics J_{sc}, V_{oc} and FF are further broken down into constituents.

3.1 Jsc losses

J_{sc} losses are attributed to reflection, glass absorption, TCO absorption, CdS absorption, and deep-penetration losses. Figure 2 shows the fraction of photons of each wavelength that contributed to Record and Production cells' short-circuit currents and the fractions that are lost by each mode listed above. The inserts show losses quantified in units of current density. These losses are listed in Table 3, and comparative analysis is done to show the impact on cell efficiency.

The short-circuit current in each case is calculated by integrating the QE spectrum multiplied by the AM1.5 solar photon current J_{solar}.

$$J_{sc} = \int_{\lambda_{min}}^{\lambda_{max}} QE(\lambda) * J_{solar}(\lambda) d\lambda \qquad (1)$$

Using Eqn. (1), an Ideal CdTe cell with band gap of 1.45 eV and QE of 100% will yield a photocurrent of 30.5 mA/cm^2. The Record and Production cells have 4.6 and 11.3 mA/cm^2 smaller J_{sc} than the theoretical maximum, respectively. Each individual current loss can be calculated using

$$J_{loss} = \int_{\lambda_{min}}^{\lambda_{max}} F(\lambda) * J_{solar} d\lambda \qquad (2)$$

where $F(\lambda)$ is fractional reflection or absorption at each wavelength. The sum of the losses plus QE must equal one at all wavelengths.

Table 3 shows the current losses due to each loss mechanism and the corresponding effect on cell efficiency. For example, a considerable J_{sc} loss for the Production cell is due to CdS absorption. The difference in final efficiency due to this effect alone is 2.3%.

3.2 Voc losses

Fundamental limitations on V_{oc} are less clearly defined. In general V_{oc} is limited by the dominant current transport mechanisms.

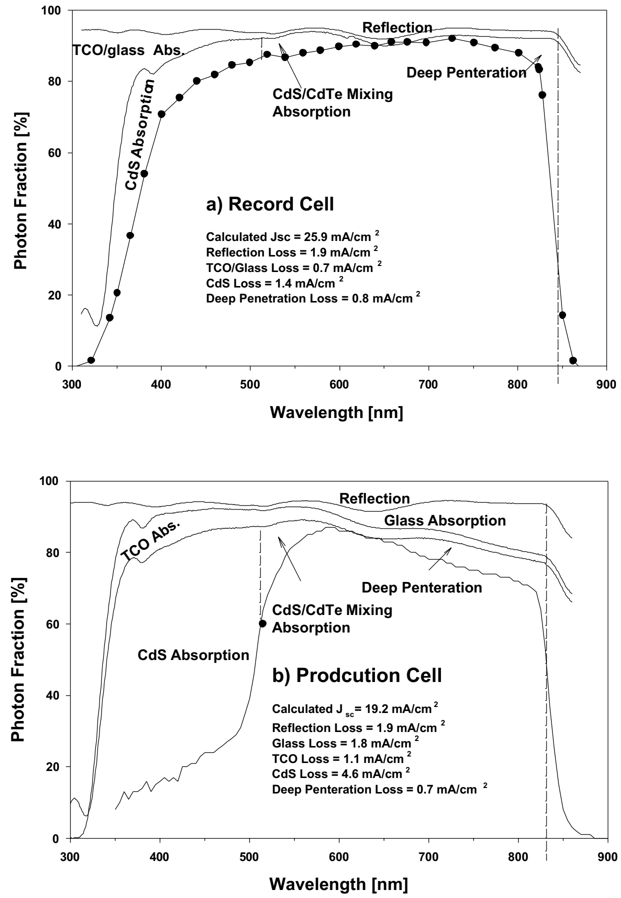

Figure 2. Photon accounting for a) Record cell b) Production cell.

Table 3. Current Losses.

	Prod.	Record	Target	R- P [Δη%]	T- R [Δη%]
J_{sc} Losses [mA/cm^2]					
Reflection	1.9	1.9	1.8	0	0.1
Galss abs.	1.8	0.7	0.3	1.4	0.2
TCO abs.	1.1	Incl	0.3	Incl	Incl
Cds abs.	4.6	1.4	1.2	2.3	0.2
Deep pene-tration.	0.7	0.8	0.6	-0.1	0.2
Total				3.6	0.7

The current-voltage characteristic of a reasonably exponential cell is described as

$$J \approx J_{00} \exp\left[\frac{q(V - V_{bi})}{AkT}\right] - J_L \qquad (3)$$

where J_L is photocurrent , J_o is the saturation current and V_{bi} is the built-in voltage. The ideality-factor A, and the current prefactor J_{oo} depend on the specific current mechanism that dominates the forward current. We assume CdTe solar cells are primarily controlled by space-charge recombination current, and hence, the flat band current J_{oo} can be expressed as

$$J_{OO} = qpv_r \tag{4}$$

where p is the hole density and V_r is a recombination velocity. Hence, V_{oc} can be expressed as

$$V_{oc} = V_{bi} - \frac{AkT}{q} \ln\left(\frac{qpv_r}{J_L}\right) \tag{5}$$

and the built-in voltage is related to the band gap by

$$V_{bi} = \frac{E_g}{q} - \frac{kT}{q} \ln\left(\frac{N_V}{p}\right) \tag{6}$$

where E_g is the band gap and N_V is the effective density of states in the valence band. Thus, for A=2:

$$V_{oc} = \frac{E_g}{q} - \frac{kT}{q} \ln\left(\frac{q^2 N_v p v_r^2}{J_L^2}\right) \tag{7}$$

Independent of the details, V_{oc} is smaller for larger recombination velocity. Hence, Improvements in V_{oc} should follow from decreased recombination. The ratio of recombination velocity to thermal velocity (v_r/v_{th}), where $v_{th} \approx 10^7$cm/s, is used as the primary recombination parameter to analyze voltage losses. Figure 3 illustrates voltage adjustments done to yield both the Record and Production cell, starting with the Ideal cell and progressively increasing the effect of recombination velocity. It is assumed that hole density will decrease with increasing recombination traps and will be equal to the value suggested by C-V measurements for the actual cells. Table 4 tabulates the estimated v_r/v_{th} values for the different cells.

3.3 FF losses.

Recombination in the depletion region can reduce the FF through the increase in A-factor and the decrease in V_{oc}. Series resistance R and shunt conductance G will also reduce the fill factor, and any voltage dependent current collection, $J_L(V)$, can additionally affect FF. For CdTe based solar cells, which have a wider depletion region, the ΔJ_L at maximum power is expected to be the order of 1% [4] and hence not be a major effect.

To analyze FF losses we have used empirical expressions that relate FF to the open-circuit voltage V_{oc}, the quality factor A, the series resistance R, and the shunt conductance G.

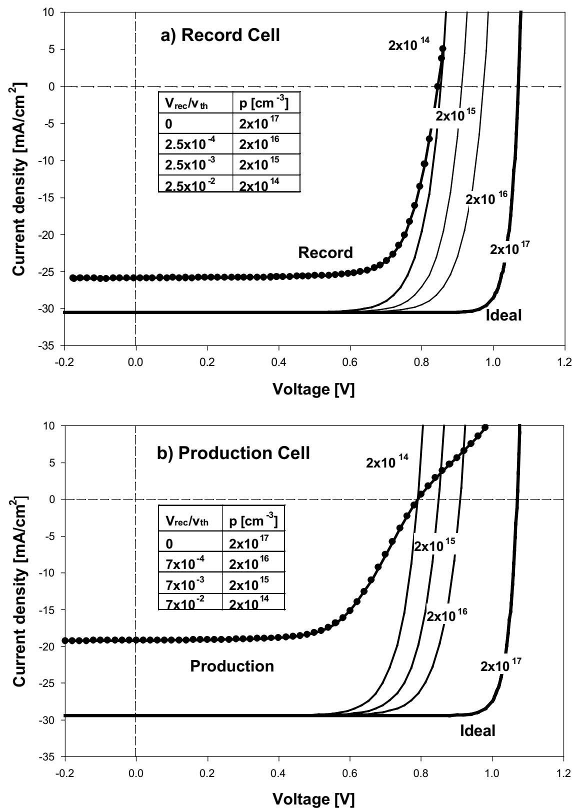

Figure 3. Voltage adjustments: a) Record b) Production cell.

Table 4. Voc Losses.

	Prod.	Record	Target	R- P [Δη%]	T-R [Δη%]
V_{oc} Losses					
v_r/v_{th}	$7x10^{-2}$	$2.5x10^{-2}$	$1x10^{-2}$	0.9	1.1

In the absence of series resistance and shunt conductance FF can be expressed as [5]

$$FF_0 = \frac{\upsilon_{oc} - \ln(\upsilon_{oc} + 0.72)}{\upsilon_{oc} + 1} \tag{8}$$

where

$$\upsilon_{oc} = qV_{oc} / AkT \tag{9}$$

In the presence of series resistance, the FF is modified by

$$FF_s = FF_0 (1 - R / R_{ch}) \tag{10}$$

where $R_{ch}= V_{oc}/J_{sc}$ is a characteristic resistance. When both series resistance and shunt conductance are significant, the expression for FF is given by

$$FF_{s+sh} = FF_s \left[1 - \frac{(\upsilon_{oc} + 0.7)FF_s}{\upsilon_{oc} / (R_{ch} G)} \right] \qquad (11)$$

Using these empirical relations, FF is calculated as each factor is added. In Figure 4 the current voltage curves are adjusted for FF losses, starting with the curve after voltage and current adjustments. In the case of the Production cell, there is an additional correction related to the back contact. The quantified FF losses due to series resistance R, leakage conductance G, quality factor A, low V_{oc}, voltage dependent current collection $J_L(V)$ and back contact are presented in Table 5.

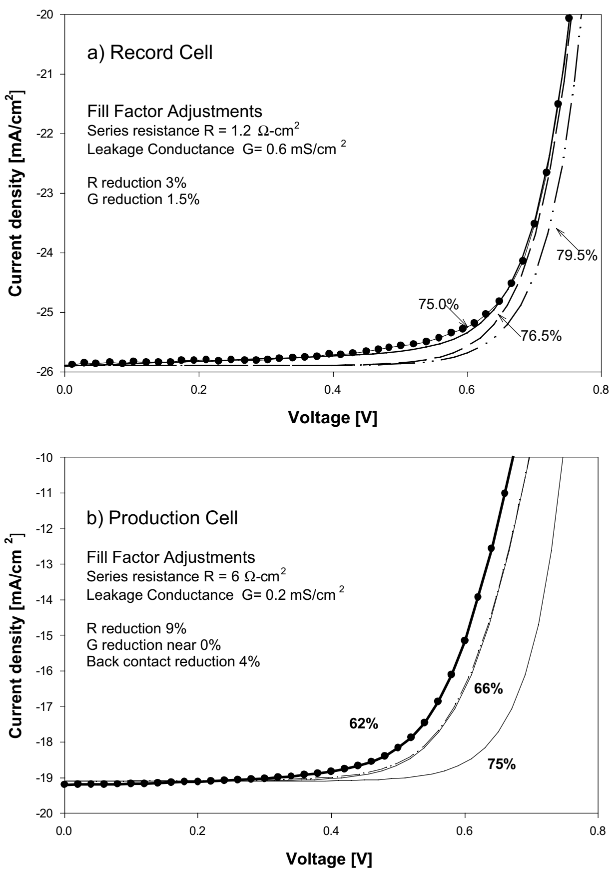

Figure 4. Effects of series resistance and leakage conductance on FF: a) Record and b) Production cell.

Table 5. FF Losses.

	Prod.	Record	Target	R-P [Δη%]	T-R [Δη%]
FF Losses					
A-Factor	2.2	1.9	1.8	0.4	0.1
R[Ω-cm^2]	6.0	1.2	0.5	1.4	0.3
G [mS/cm^2]	0.2	0.6	0.3	-0.1	0.1
J_L (V) [FF %]	1.0	1.0	1.0	0	0
Low V_{oc}[FF%]	3.2	2.4	1.8	0.2	0.2
Back contact [FF %]	3.8	0	0	0.5	0
Total				2.4	0.7

4. DISCUSSION

To identify the major performance losses in CdS/CdTe solar cell performance, we have presented "third-level metrics", as a systematic way of evaluating the losses. This method breaks down the fundamental photovoltaic parameters (J_{sc},V_{oc} and FF) into their constituents. The individual losses are expressed both as a deficiency in the specific parameter and as the impact on cell efficiency. The latter allows clear identification of the most significant losses. The loss quantification mostly gives firm parameters for the different CdTe cells, but some of the loss values rely on educated estimates. For the Record cell, the dominant problem is voltage loss (recombination current). For the Production cell, is also its window, glass/TCO absorption and the series resistance. Analysis of third-level metrics suggests that a 19% efficient Target cell is feasible with voltages only slightly above those already achieved and with modest improvements elsewhere.

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