Device Physics of Thin-Film Polycrystalline Cells and Modules

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SUMMARY

Progress has been made in several applications of device physics to thin-film polycrystalline cells and modules. At the cell level, results include a more quantitative separation of photon losses, the impact of second barriers on cell operation, and preliminary studies of how current-voltage curves are affected by band offsets. Module analysis includes the effects of the typical monolithic, series-connected cell geometry, analytical techniques when only the two module leads are accessible, and the impact of chopping frequency, local defects, and high-intensity beams on laser-scanning measurements.

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INTRODUCTION

The objectives of the Colorado State program are (1) the separation and quantification of individual loss in specific thin-film solar cells, (2) the detailed characterization of small modules, and (3) the presentation of a viable model for the forward-current loss mechanism. Progress was made in each of these areas.

Four research students, Xiaoxiang Liu, Ingrid Eisgruber, Jennifer Granata, and Gunther Stollwerck were responsible for most of the experimental and analytical work. In addition, two first-year students, Jon Sharp and Brendon Murphy, worked in the lab during the summer, and Prof. John Scofield from Oberlin College participated in many of the capacitance measurements. Ms. Liu completed her Ph.D. in June and now teaches at Front Range Community College while continuing part-time research at Colorado State. Mr. Stollwerck complete his M.S. in December and has returned to the ISE in Freiburg.

The Colorado State program continues to collaborate closely with a number of other laboratories. During the past year active collaborations have include the Institute of Energy Conversion, International Solar Electric Technology, Inc., the National Renewable Energy Laboratory, Solar Cells, Inc., Siemens Solar Industries, Solarex, ANTEC in Germany, Energy Photovoltaics, Inc., and Oberlin College. Particularly helpful during the past year has been the assistance of Prof. Jeffery Gray of Purdue University in sharing the ADEPT software and answering numerous questions.

CELL ANALYSIS

Photon Losses

A major effort has been made to quantitatively account for all photon losses with an uncertainty of no more than a few tenths of a mA/cm^2 in equivalent photocurrent [1]. The cornerstone of the equipment upgrade was the replacement of a filter-wheel quantum-efficiency system by one based on a small, high-light-throughout monochromator. The entire apparatus (see Fig. 1) is mounted on the side of the lab's primary light box, so that current-voltage, quantum efficiency, and capacitance can all be measured without disturbing the cell or the probes. In general, quantum efficiency is measured at zero bias by superimposing the monochromator light on a $100 \text{ mW}/\text{cm}^2$ white-light background.

Figure 1. Quantum efficiency measurement.

The monochromator output is focused to an area of 0.1 cm^2 , so that in most cases, the entire beam strikes the active area of the cell being measured. Additional photocurrent generated by the monochromator peaks at $40 \mu\text{A}$. There was some initial difficulty with second-order transmission when the monochromator was set below 400 nm , but the unwanted transmission was effectively suppressed by masking part of the focal mirror. Calibration is done in three ways: a constant output diode laser, a thermopile, and a reference cell. Of these, the reference cell has proven most reliable. Final normalization requires the quantum efficiency curve to be consistent with the measured short-circuit current.

The additional information needed to separate and quantify the photon losses comes from optical transmission and reflection measurements. If samples are available following each layer of cell deposition, or if one can etch back a layer at a time, the individual photon losses may be identified with a reasonable level of precision. Figure 2 shows the absorption by each material that light passes through in a CdTe cell. There are different levels of sophistication involved in the analysis process depending on how complete a model of reflection from multiple interfaces is used, but in general the loss assigned to each layer is not highly dependent on the model.

Figure 3 combines the measured quantum efficiency with the optical measurements to account for all the photons of each wavelength. A very useful calculation is to integrate the area attributed to each loss, weighted by an appropriate spectrum. If the spectrum is expressed in equivalent current-density units, the integral is the individual photocurrent loss for the specified region. The table below the figure gives the photocurrent losses for the standard AM1.5 global spectrum, but one can use the same data to calculate the losses for the AMO, or any other spectrum.

The photon-loss breakdown, such as illustrated in Fig. 3, is designed to give manufacturers a convenient format to compare the different losses and evaluate the potential gains related to fabrication modifications. In most cases, the uncertainty in the loss associated with each region is a few tenths of a mA/cm^2 . In some cases, however, the individual losses simply do not add

Figure 2. Transmission through CdTe cells terminated at four stages (top) supplemented by reflection (bottom) is used to calculate the photon absorption in each layer (middle).

CdTe solar cell

J_{sc}	Reflection loss	Glass absorp.	SnO ₂ absorp.	CdS loss	Deep penetr.	Max. photo current
17.6	1.7	2.0	2.4	5.8	1.1	30.6

all currents in mA/cm²

Figure 3. Quantum efficiency and photon losses for a Solar Cells, Inc. CdTe cell.

up, and the residual is labeled "unknown" and assumed to be wavelength independent. In other cases, direct optical information from individual layers is not available, but intelligent estimates can often be used to construct plots like Fig. 3 with some increase in uncertainties.

Second-Barrier Effects

A fairly common feature of polycrystalline thin-film current-voltage curves is a current-limiting effect in the forward current region that becomes progressively more important as temperature is decreased. Figure 4 illustrates this effect for a CdTe cell made by ANTEC. In this case, the data can be fit quite well with the band structure and circuit model shown in Fig. 5 [1]. The necessary features of the circuit element labeled "back-contact diode" are (1) it has opposite polarization to the primary photodiode, (2) it has a barrier height of approximately 300 meV,

Figure 4. Temperature dependence of second-barrier effect seen in ANTEC CdTe cells.

(3) it is not light active, and (4) it exhibits significant leakage. Collectively these features are highly suggestive of the hole barrier at the back contact shown in Fig. 5.

Figure 5. Band structure and circuit model consistent with data shown in Fig. 4.

The practical question about the second barrier is whether it has an impact on the power output of the solar cell. At the barrier magnitude illustrated in Fig. 4, there is negligible change in V_{OC} or J_{SC} but there is a decrease in fill factor from 0.67 to 0.64 at room temperature, which corresponds to an efficiency loss of about 0.5%. Figure 6 illustrates the impact on fill factor and efficiency as a function of barrier height. There is no measurable effect for barriers below 250 mV at room temperatures. (For other temperatures, the x-axis labels in Fig. 6 should be multiplied by $T/300$).

Most CdTe cells measured at Colorado State have second-barrier heights of 250 mV or less, and hence no measurable effect on the power output. Many $CuInSe_2$ cells also show an effect similar to Fig. 4 at a lower range of temperatures, implying small barriers. Some $CuInSe_2$ cells, however, show a barrier effect of the opposite polarity that disappears under blue light. These cells are still under study and will be discussed in a later report.

Figure 6. Variation in fill factor and efficiency with height of second barrier.

Band Offsets

The conduction-band offset ΔE_C between CdS and CuInSe₂ (or CIGS) has historically been assumed to be near zero, but recent measurements [2,3] have suggested that this may not be the case. To put this question in a practical context, we have calculated the band diagram and the current-voltage curves for the CdS/CIGS diode as a function of band offset. These calculations utilize the ADEPT software [4] developed at Purdue University with parameters appropriate to commonly fabricated cells. An absorber bandgap of 1.15 eV is assumed, but the conclusions should be only weakly bandgap dependent.

Figure 7 shows the zero-bias band diagrams for band offsets spanning the range of reasonable interest. The positive offset in this convention sharpens the barrier at the materials interface; the negative barrier introduces a spike. Since the depletion width, or field-collection region, is clearly larger for negative offset, one would expect a larger photocurrent. In fact

Figure 7. Calculated CDS/CIGS band diagram for three selected band offsets.

Fig. 8 shows a smooth increase of short-circuit current as the offset is changed from positive to negative. The variation over the entire range, however, is less than 10%, so deduction of the band offset from the measured J_{SC} , which is influenced by a number of factors, is not a practical procedure.

Open-circuit voltage, which is determined in part by the forward-current density, also shows a modest dependence on band offset. Figure 9 shows the band diagram near V_{OC} for positive offsets. These offsets provide a barrier to forward-current electrons (approaching from the CdS side). Hence, forward current is lower and V_{OC} higher. Similarly, with negative offsets (Fig. 10), the barrier for forward-current holes (approaching from the CIGS side) is higher, and once again forward current decreases and V_{OC} increases. In both cases the increase is less than 20 mV, as seen in Fig. 8 summary.

Figure 8. CIGS cell parameters as a function of conduction-band offset.

Figure 9. Band diagram near V_{OC} for positive band offset.

Figure 10. Band diagram near V_{OC} for negative band offset.

Fill factor also changes relatively little with offset over a fairly wide range, and it tends to track the open-circuit voltage, as one might expect. At large forward offsets, however, it decreases significantly, and at a negative offset near -0.4 V it drops precipitously. Figure 11 illustrates the fill-factor behavior, which is also summarized in Fig. 8.

The conclusion from these preliminary studies is that solar-cell efficiency is relatively insensitive to band offset over a fairly wide range at room temperature. Additional projects are underway to apply ADEPT to two other systems: (1) the inclusion of an indium-rich layer with layer bandgap than CuInSe_2 , and (2) the possibility of a photoinduced change in the CdS carrier concentration.

Figure 11. Gradual and sudden deterioration of fill-factor as conduction-band offset is pushed in positive and negative directions.

MODULE ANALYSIS

Cell Geometry

A general, and probably inherent, feature of polycrystalline thin-film analysis is that the cell geometry is fundamentally different from optimized individual cells or the cells used in crystalline silicon modules [5]. Essentially all manufacturers have focused on a monolithic module consisting of gridless, series-connected cells that are 0.5–1 cm wide (x-direction) and as long (y-direction) as the module (see Fig. 12). This geometry has only a single grid line at the edge of the transparent conductive oxide (TCO) used as the top contact. For the geometries

Figure 12. Module cell geometry. Thick line shows top contact.

and TCO layers in current use, the voltage drop across the TCO is 40–100 mV at operating conditions, which corresponds to an effective resistance of 2–5 $\Omega\text{-cm}^2$. Generally, the voltage drop across the back, or bottom, contact can be assumed to be negligible.

Figure 13 compares the current-voltage curves for a research-geometry and a module-geometry CdTe cell fabricated under nominally identical conditions. Obviously, there is a significant

Figure 13. Current-voltage curves for research-geometry and module-geometry CdTe cells.

penalty in fill factor. The effective series resistance can be lowered with thinner cells, but at the expense of lost real estate for the additional interconnects. It can also be lowered by a lower sheet-resistivity TCO, but here the price is an increase in TCO optical absorption.

In addition to the efficiency loss due to the TCO voltage drop, there is a complication for reliable cell analysis. Basically, when the voltage drop shown in Fig. 12 is sufficiently large, the single-parameter series-resistance approximation fails. The parameter that determines the validity of the approximation is $w^2\rho_S$ where w is the cell width and ρ_S is the TCO sheet resistance. Figure 14 shows what happens for a CdTe cell with typical parameters, including a diode quality factor of 2.0. The arrows at the top indicate typical values of $w^2\rho_S$ for research- and module-geometry cells. As the single-parameter series resistance fails, one gets a progressively larger overestimate of the quality factor and corresponding underestimate of the series resistance. These differences will be accentuated if the cells also happen to be leaky.

Quantum efficiency measurements on module cells can also give misleading results. For substrate cells, the measurement contacts are typically probes to the TCO layer of adjacent cells. This probe geometry has a load resistant $R_L \sim 10 \Omega$. At the same time, the shunt resistance is inversely proportional to cell area, so for a typical shunting of $1000 \Omega\text{-cm}^2$, the actual shunt resistance of a 10-cm^2 cell is 100Ω . The measured quantum efficiency (QE_M) is related to the actual value (QE) by

$$QE_M = QE / (1 + R_L / R_{sh}) .$$

For the case described, the measured value will be 10% low. For longer module cells, the discrepancy becomes larger.

Cell-to-Cell Variations

Cell-geometry effects will impact all module cells, even if the cells can be contacted individually. In general, however, one may need to test modules where only the two leads to the module are accessible. In this case, laser-scan, or optical-beam-induced-current (OBIC),

Figure 14. Effect of cell width and TCO sheet resistance on the apparent diode quality factor and series resistance for typical CdTe cells. Open circles are for standard illumination; filled circles for dark circles.

measurements are appealing, since the light can be easily moved from one cell to another. There are several pitfalls, however, in the interpretation of these measurements [6]. Figure 15 shows an OBIC scan across an 8-cell CdTe module. There is structure across each cell

Figure 15. Measured and predicted OBIC signals from a small CdTe module at short circuit. (a) No bias light. (b) Modest white-light bias.

representing changes in photocurrent, but the large variations in OBIC signal between cells are artificial and due to variations in shunt resistance among the cells. The measured OBIC signal is weighted by the shunt resistance of the cell in much the same way as the quantum efficiency correction described above. The predicted curve, based on individually measured shunt resistances, gives a reasonable fit, especially since shunting can be modified by illumination. Laser scan with bias light (Fig. 15b) introduces two additional complications: (1) the variation of shunting with light intensity is not consistent from one cell to another and (2) modest non-uniformity in bias-illumination intensity can significantly change the distribution of voltage bias from cell to cell, and hence the voltage at which shunt resistance is measured. The Fig. 15b scan uses exactly the same cells as the 15a scan, but there are very substantial changes in both the measured and the predicted variations.

Chopping Frequency

Lock-in detection often used for OBIC measurement both to increase sensitivity and to allow measurements in lab areas that are not completely darkened. For single cell measurements, the circuit frequency $(2\pi RC)^{-1}$ is typically the order of 100 kHz, since $R \sim 1 \Omega$ for most measurement inputs. If there are additional module cells in series, however, $R \sim 1 \text{ k}\Omega$, the shunting resistance of the other cells. Thus, the circuit frequency is the order of 100 Hz, and a significant capacitive component to the measurement signal must be anticipated.

A potential advantage of the chopping-frequency effect is that the signal weighting by cell-to-cell variation in shunting resistance (Fig. 15) is replaced by a capacitance weighting at higher frequencies. Since cell-to-cell variations in capacitance tend to be much smaller than shunt-resistance variations, high-chopping-frequency OBIC should yield a true photocurrent map even when only the two end cells are accessible. In practice, mechanical chopping frequencies generally available do not reach the high-frequency limit, but OBIC measurement

as a function of chopping frequency can be extrapolated to produce the photocurrent map of the module.

Defect Signatures

There are two basic types of cell defects: local shunts and photocurrent dead areas. In practice, the individual shunts in a module cell rarely have a resistance less than 1 k Ω and are far from being "shorts." Otherwise the cell or module is likely to have a serious reduction in output and be rejected early in the screening process. The OBIC signal in the vicinity of a 1-k Ω shunt is reduced, but only by about 1%. Furthermore, the physical nature of most shunts, scratches or foreign material, tends to also cause a dead area for photocurrent, i.e., a local reduction of 100%. Thus, essentially all defects detected by OBIC have the primary signature of a photocurrent dead area whether or not a shunt is also present. Stated in other words: shunts have a much greater impact on the current-voltage curve than can be independently determined from the OBIC data.

High Intensity Effects

Figure 16 shows two laser line scans on part of a 52-cell CuInSe₂ module. One scan has a beam intensity much greater than the other. The high-intensity scan has a much less uniform appearance. Furthermore, it tends to have a maxima at edge of the individual cells. The greater non-uniformity is due to variations in the bulk-semiconductor or back-contact resistance, or to local focusing and defocusing of the beam by the morphology of the cell surface. A focused area, or a high-resistance area, will drive the cell further into forward bias locally and hence show a decrease in apparent quantum efficiency. The converse can be demonstrated by aiming the beam at a dust particle, which spreads the beam and gives an enhanced signal. The maxima at the edges are due to light scattered onto adjacent cells, which are efficient collectors, because they have been pushed into farther reverse bias by the higher signal current.

Figure 16. Laser scan of a module at (a) high beam intensity, (b) low beam intensity.

The decrease in apparent quantum efficiency with beam intensity can in principle be used as a tool to separate resistance in the TCO resistance from bulk-absorber resistance or back-surface contact resistance. These two components perpendicular to the cell's surface will determine which of the Fig. 17 curves the measured quantum efficiency will follow as a 5-mW beam is focused to a smaller spot size. In practice, this procedure works at the qualitative level, but there are enough assumptions in the process that it is questionable whether reliable resistance values can be extracted.

Figure 17. Apparent quantum efficiency as a function of beam intensity and resistance perpendicular to cell surface.

EFFICIENCY, PROGRESS AND OUTLOOK

Figures 18 and 19 summarize the reductions in losses and subsequent efficiency improvements for CdTe and CIGS cells in recent years. The format used is maximum-power current density

Figure 18. Summary of CdTe efficiency increases and breakdown of remaining losses.

vs. maximum-power voltage for the standard 100 mW/cm² global spectrum. The increase in rectangle area is the recent efficiency improvement; the dashed-rectangle area is the theoretical maximum efficiency.

Figure 19. Summary of CIGS efficiency increases and remaining losses.

For CdTe cells (Fig. 18), there has been significant current improvement through the use of thinner CdS in the window layer and significant voltage improvement because forward current due to junction recombination has been reduced by a factor of 5. Smaller increases in current have resulted from lower absorption glass and TCO and in maximum-power voltage from reductions in series resistance of the cell. The remaining current losses for CdTe, which are quantified by the numbers in parentheses, are primarily optical. Because the absorber depletion is relatively wide for most CdTe cells, field-driven collection tends to be quite high. By far the largest remaining voltage loss is due to forward current, which continues to be enhanced by junction recombination. There is, incidentally, some coupling between maximum-power current and voltage, so that an increase in one automatically gives a small increase in the other.

Much of the improvement with CIGS (Fig. 19) has resulted from junction quality: in this case there has been a 25-fold decrease in forward recombination current. There have also been modest improvements in a number of other factors as shown. When considering additional efficiency improvements, bulk collection, window absorption, and junction quality are the obvious targets. There is likely in fact to be some coupling between bulk collection and junction quality because both should improve with better passivation of extraneous states in the bandgap.

RECOMMENDATIONS

The first recommendation is for an expansion and refinement of straightforward techniques to characterize modules. This has been an extremely fertile field during the past year and one that is yielding significant return on modest investment.

A second, related recommendation is to encourage module makers to include test points for individual cells in the module design. Techniques for analyzing a module with only end connections are evolving, but they tend to be more complex and less reliable than individual-cell access.

A third, and continuing, recommendation is for increased exchange of data and details of analytical techniques among the thin-film polycrystalline community. A growing number of exchanges are taking place. Essentially all the problems have been solved at the conceptual level, but the community is still far from routine exchange.

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COMMUNICATIONS

Publications

1. "Status of Polycrystalline Thin-Film Solar Cells," AIP Conf. Proc. 308, 407 (1994). I. L. Eisgruber and J. R. Sites.
2. "The Large-Scale Laser Scanner: Milli-Characterization of Photovoltaic Devices and Modules," Proc. European Photovoltaic Solar Energy Conf. 12, 1222 (1994). R. J. Matson, K. A. Emery, I. L. Eisgruber, and L. L. Kazmerski.
3. "Six-Year Efficiency Gains for CdTe and $\text{CuIn}_{1-x}\text{Ga}_x\text{Se}_2$ Solar Cells: What Has Changed?" Proc. 1st World Photovoltaic Energy Conf. (1994). J. R. Sites and X. X. Liu.
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5. "Effect of Thin-Film Module Geometry on Solar Cell Current-Voltage Analysis," Proc. 1st World Photovoltaic Energy Conf. (1994). I. L. Eisgruber, R. J. Matson, J. R. Sites, and K. A. Emery.
6. "Interpretation of Laser Scans from Thin-Film Polycrystalline Photovoltaic Modules," Proc. 1st World Photovoltaic Energy Conf. (1994). I. L. Eisgruber, R. J. Matson, J. R. Sites, and K. A. Emery.

Ph.D. Thesis

"Current Transport With and Without Gain-Boundary Recombination for Polycrystalline CuInSe_2 Solar Cells," Xiaoxiang Liu, Colorado State University, Summer 1994, unpublished.

Talks

1. Colorado State University	Ft. Collins, CO	Sites	January 1994
2. Institute of Energy Conversion	Newark, DE	Sites	March 1994
3. Solarex	Newtown, PA	Sites	March 1994
4. Energy Photovoltaics	Princeton, NJ	Sites	March 1994

5. Siemens Solar Industries	Canirillo, CA	Sites	July 1994
6. Solar Cells, Inc.	Toledo, OH	Sites	September 1994
7. Oberlin College	Oberlin, OH	Sites	September 1994
8. Dept. of Energy Review	Denver, CO	Sites	October 1994
9. WPVEC-1	Kona, HI	Sites	December 194

Specific Cell/Module Reports

<u>Date</u>	<u>Cell Type</u>	<u>Organization/Individual</u>	<u>Cell/Module Studied (or other meas.)</u>
1/13/94	CdTe	SCI/Meyers	L9305CJ (mod)
1/25/94	CIGS	NREL/Contreras	C226-23 #8
2/21/94	CIGS	NREL/Contreras	C226-23 #8,5
3/04/94	CdTe	SCI/Meyers	9511F6 #32
3/10/94	CdTe	NREL/Matson, Energy	SCI module
3/25/94	CIS	EPV/Delahoy	9-21-1-3B
3/25/94	CIS	IEC/Phillips	32220-22-5
4/06/94	CdTe	SCI/Sasala	9504J1 + layers
4/18/94	CdTe	SCI/Sasala	L9820J2 (mod)
4/22/94	CdTe	SCI/Sasala	9504 J1
5/05/94	CIS	ISET/Basol	4-pt. meas.
5/13/94	CdTe	ANTEC/Bonnet	N111
5/18/94	CdTe	SCI/Sasala	L9820J2 (mod)
5/26/94	CIS	ISET/Basol	1502(6); 1505(6)
6/23/94	CdTe	SCI/Sasala	9504 J1
7/14/94	CIS	SSI/Gay, Willet	100B-72 (cells) 100B-2 (mod)
8/08/94	CIS	SSI/Willet	same
9/25/94	CIS	SSI/Tarrant	Shunts

9/28/94	CIS	Solarex/Kessler	189, 250, 221, 251
10/07/94	CIS	Solarex/Kessler	189, 250, 221, 251
10/07/94	CdTe	SCI/Sasala	R _S separation
10/18/94	CIS	SSI/Willet	100B-72
10/21/94	CdTe	SCI/Sasala	CDs optics
11/01/94	CIS	Solarex/Kessler	Second diode
11/02/94	CdTe	CSU/Sampath	Local cells
11/21/94	CdTe	SCI/Sasala	R _S separation
11/25/94	CIS	SSI/Willet	90B49 (mod)
12/02/94	CIS	ISET/Basol	1646

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13. ABSTRACT (Maximum 200 words) This report describes work performed under a subcontract to (1) separate and quantify the individual loss in specific thin-film solar cells, (2) characterize in detail small modules, and (3) present a viable model for the forward-current loss mechanism. Progress was made in several applications of device physics to thin-film polycrystalline cells and modules. At the cell level, results include a more quantitative separation of photon losses, the impact of second barriers on cells operation, and preliminary studies of how current voltage curves are affected by band offsets. Module analysis includes the effects of the typical monolithic, series-connected cell geometry, analytical techniques when only the two module leads are accessible, and the impact of chopping frequency, local defects, and high-intensity beams on laser-scanning measurements.					
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