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Conference Paper

An On-Sun Comparison of $GaInP_2$/GaAs Tandem Cells with Top Cell Thickness Varied

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AN ON-SUN COMPARISON OF $GaInP_2$/GaAs TANDEM CELLS WITH TOP CELL THICKNESS VARIED

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ABSTRACT

This study compares the on-sun performance of a set of $GaInP_2$/GaAs tandem cells with different $GaInP_2$ top-cell thicknesses. Because high-efficiency III-V cells are best suited to concentrating photovoltaic (CPV) applications, the cells were mounted on a two-axis tracker with the incident sunlight collimated to exclude all except the direct beam. Current-voltage (I-V) curves were taken throughout the course of several days, along with measurements of the direct solar spectrum. Our two major conclusions are: (1) $GaInP_2$/GaAs tandem cells designed for an "air mass 1.5 global" (AM 1.5G) or a "low aerosol optical depth" (Low AOD) spectrum perform the best, and (2) cells can be characterized indoors and modeled using outdoor spectra to predict the correct result. These results are equally valid for $GaInP_2$/GaAs/Ge triple-junction cells.

INTRODUCTION

To maximize the performance of $GaInP_2$/GaAs tandem cells and $GaInP_2$/GaAs/Ge triple-junction cells, the top $GaInP_2$ cell must be "thinned" slightly to allow some above-band-gap photons to pass through to the GaAs bottom cell. Because the solar spectrum changes throughout each day, the optimal top-cell thickness (t_{top}) constantly changes. Nonetheless, when tandem cells are manufactured for use in a concentrator system, a single t_{top} must be specified. This study is intended to aid in t_{top} selection for CPV applications.

The first half of this paper compares the performance of real $GaInP_2$/GaAs tandem cells as a function of t_{top}, under direct outdoor sunlight. Measurements were taken over the course of several days to study how changing spectral content affects performance. In general, we find that $GaInP_2$/GaAs tandem cells designed for an AM 1.5G or a Low AOD spectrum perform the best. These results agree well with a previous theoretical study [1], in which we simulated the performance of $GaInP_2$/GaAs tandem cells under "standard day conditions" as a function of t_{top}.

In the second half of this paper, we obtain the same results theoretically by carefully characterizing the same set of cells and applying a simple device model. This modeling also allows us to theoretically decouple the top- and bottom-cell photocurrents, so as to clearly illustrate the importance of "current matching" for tandem cell performance.

Measurements were made on clear days in Golden, Colorado (40°N, 105°W, 1830m). To a first approximation, they represent the spectral variation of sunlight at a typical concentrator site in the southwestern United States.

EXPERIMENTAL DETAILS

To give some background, the model results in Fig. 1 show how performance should vary with t_{top} under four standard reference spectra [2]. For each spectrum, there is an optimal t_{top}.

For this study, we grew a set of tandem cells (named 'A' - 'E') with five different top-cell thicknesses, with a t_{top} range spanning all foreseeable applications. Approximate

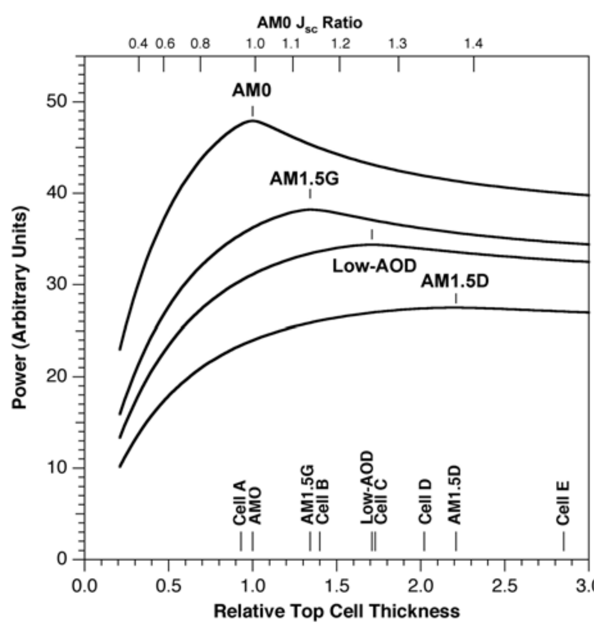

Fig. 1. Calculated power produced by a GaInP/GaAs/Ge triple-junction cell as a function of t_{top} for Air Mass 0, 1.5 Global, 1.5 Direct, and Low Aerosol Optical Depth standard reference spectra. Relative t_{top} values are shown, normalized to the optimal AM0 t_{top}. Although the power produced by a GaInP/GaAs tandem cell will be less, the optimal t_{top} for any given spectrum will not change. Approximate t_{top} values for cells A - E are indicated.

t_{top} values for these cells are shown along the bottom axis. Cell A has the thinnest t_{top} and is well suited to "blue-rich" space applications. Cell E has the thickest t_{top} and is better for "red-rich" morning and evening light. The other three cells have intermediate t_{top} values which are compromises between midday power production and overall daily energy production. As a gauge of experimental error, two cells were grown with the median t_{top} (C1 and C2). Cell C should perform best under a Low-AOD spectrum [3] proposed for concentrator applications. A "clear sky" direct spectrum which is similar to the Low-AOD spectrum has also been proposed [4].

The cells were then mounted on a two-axis tracker, with the incident sunlight collimated to exclude all except the direct beam. The collimators followed the design shown in the annex of Ref. [5], with a 5° field of view. No protective glass, antireflection coatings, nor bypass diodes were used.

The cells were actively cooled to a nominal temperature of 25° to 30° C, and I-V measurements were made for each cell throughout the day. To facilitate cell modeling, the direct solar spectrum was measured concurrently using a collimated spectrometer mounted on a two-axis tracker.

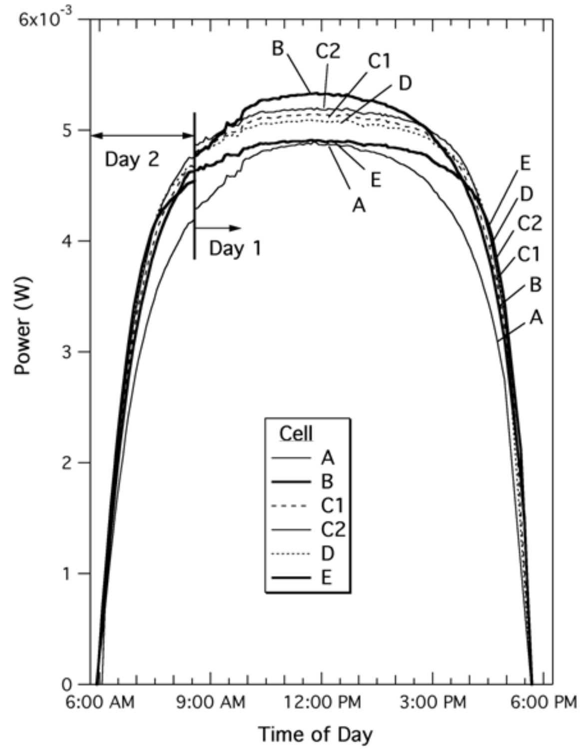

Fig. 2. Measured powers for cells A - E on Sept. 23-24, 2004, at NREL, in Golden, Colorado. Because no morning data were taken the first day, data from the morning of the second day are substituted. Cells are labeled in the order of performance midday and during the evening. The cell area for each cell is 0.253 cm^2.

EXPERIMENTAL RESULTS

Figure 2 shows the power produced by each cell on a particularly clear (blue-rich) day. Cell B (designed for ~AM1.5G) was best for midday power production, whereas cell E performed best during the morning and evening. Cell A (designed for ~AM0) is out-performed by other cells throughout the day. Although not shown here, the measured midday power for cells B and C during slightly hazy, partly cloudy days was approximately the same.

The power produced by each cell over the course of the day shown in Fig. 2 was integrated to determine its daily energy (Table 1). If cells C1 and C2 are averaged, the daily energies for cells B and C are about the same. On a slightly hazy, less blue-rich day, cell C is favored.

Cell	t_{top} (relative)	Energy (Wh)	Relative Energy (%)	Design Spectrum (approx.)
A	0.93	0.4626	89.51	AM 0
B	1.40	0.5140	99.46	AM 1.5 G
C1	1.73	0.5082	98.34	Low AOD
C2	1.73	0.5168	100.00	Low AOD
D	2.02	0.5092	98.53	--
E	2.85	0.4988	96.52	--

Table 1. Daily energy calculated by integrating the measured power for each 0.253-cm^2 cell over the test day shown in Fig. 1. The t_{top} values are approximate.

MODEL DETAILS

To better understand the experimental results, we applied a simple device model to the same set of cells. The semi-empirical model we used needed three inputs: (1) the measured outdoor spectra as a function of time of day, (2) the measured top- and bottom-cell external quantum efficiencies as a function of photon wavelength, and (3) the thicknesses of the top and bottom cells, used only to estimate their dark currents.

Some representative direct spectra taken during the test day. are shown in Fig. 3. To discuss these spectra, it is useful to divide the spectra into "blue" photons above (in energy) the GaInP band gap and "red" photons between the GaAs and GaInP band gaps. The ratio of blue to red light is highest during the midday hours, favoring a tandem cell with a thin top cell. In the morning and evening, the direct spectra become "red-rich" so a thicker top cell is better. In a triple-junction GaInP/GaAs/Ge cell, the Ge junction is generally over-supplied with photons below the GaAs band gap. For this reason, the conclusions of this paper apply equally to GaInP/GaAs/Ge triple-junction cells.

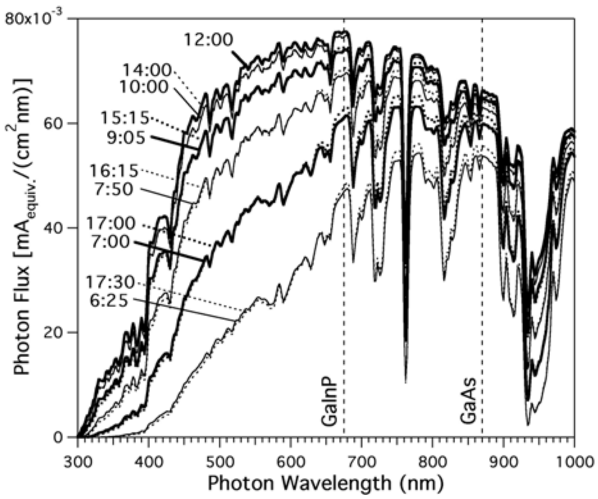

Fig. 3. Measured direct spectra labeled by time of day during the test day. The photon flux is expressed as mA equivalent for 100 percent conversion of photons to photocurrent, per cm^2 area and nm of wavelength. The GaAs and GaInP band gaps are indicated with vertical dashed lines. Morning spectra are plotted with solid lines. Afternoon and evening spectra are plotted with dashed lines.

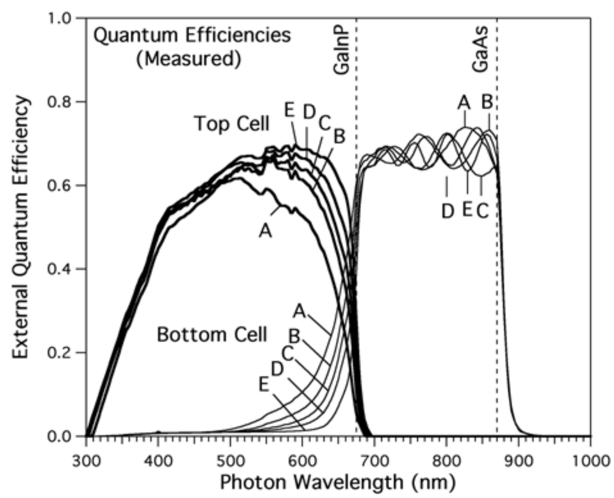

Fig. 4. Measured external quantum efficiencies for the top and bottom cells. Cell C is represented by C2. (Cell C1 data is not shown.)
A small non-physical sub-band-gap top cell response was removed by smoothly setting the top cell QE to zero for wavelengths greater than ~700 nm.

As an aside, it is interesting to note the differences between morning and afternoon spectra. In each plotted pair, (7:00 and 17:00, for example), the afternoon spectrum (dashed) is more red-rich. This is not too surprising, since the atmospheric conditions in the morning are generally different from those in the afternoon and evening.

Measured top- and bottom-cell external quantum efficiencies (QEs) are shown in Fig 4. The top-cell QE was measured by using a bias light to over-supply the bottom cell with photocurrent. The tandem cell is therefore strongly top-cell limited, so the response to a second light source can be monitored as a function of photon wavelength to obtain the top-cell QE. A similar procedure is used to measure the bottom-cell QE. A description of this technique can be found in ref. [6].

Above the GaInP band gap, both the top- and bottom-cell QEs change with t_{top}. As the t_{top} increases (from A to E), the top cell QE increases and the high-energy tail of the bottom cell QE decreases.

Below the GaInP band gap, there is no optical absorption by the top cell, so the bottom-cell QE does not change with t_{top}. However, multiple reflections of sub-band-gap light through the top GaInP cell leads to interference fringes in the bottom-cell QE. As t_{top} increases, the period of these fringes decreases. Because the amplitude of these fringes is fairly small, they should not complicate our results. For anti-reflection coated cells, these fringes and their effects will become completely negligible.

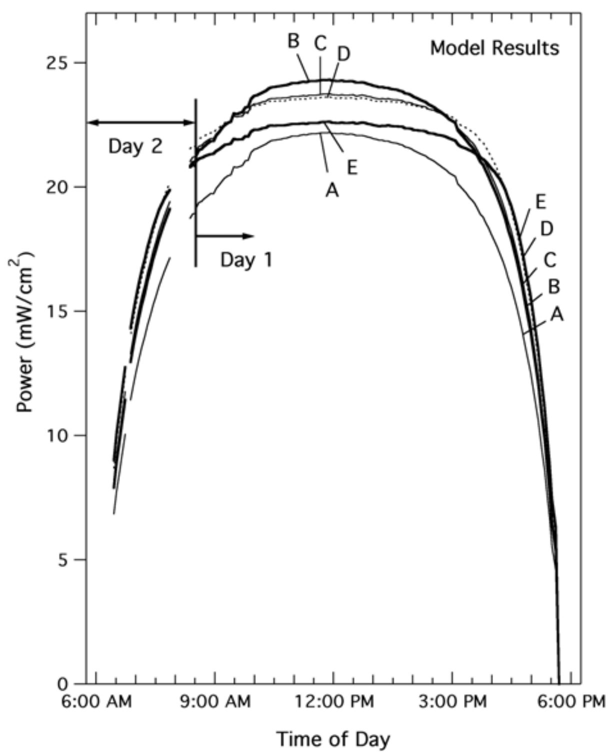

Fig. 5. Model results for the test day shown in Fig. 2. Gaps in the curves occur whenever the direct spectra was not recorded.

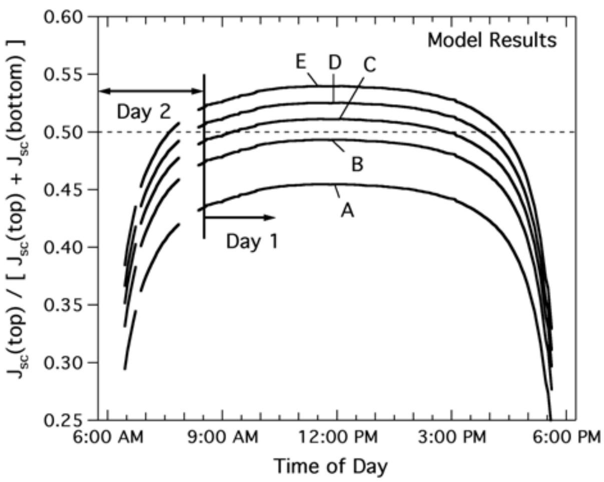

Fig. 6. Modeled decoupled short-circuit currents (plotted as a ratio) during the test day. The best power production is for a current-matched cell with a ratio of 0.5.

MODEL RESULTS

The QEs of Fig. 4 were convoluted with the measured direct spectra of Fig. 3 to give decoupled top- and bottom-cell short circuit currents [J_{sc}(top) and J_{sc}(bottom)]. These J_{sc} values were then fed into standard diode equations to generate tandem-cell I-V curves. The resulting power at the maximum power point for each I-V curve is plotted in Fig. 5. These results and the experimental results (Fig. 2) are in very good agreement. This sort of modeling can therefore serve as a quick and convenient supplement to actual outdoor cell measurements under various conditions.

Modeling can also be used to illustrate how current matching changes throughout the day, directly affecting the tandem-cell performance. The ratio $J_{sc}(top)/[J_{sc}(top)+J_{sc}(bottom)]$ is plotted in Fig. 6 as a function of time of day for each cell. Maximum performance occurs when this ratio is 0.5 (dashed line). This can be confirmed by noting that midday power performance in Figs. 2 and 5 is (from best to worst): B, C, D, E, A. This correlates well with the midday distance from the dashed line at 0.5 in this figure.

However, cell C produces more energy than cell B over the course of the day (Table 1). This is because the curve for cell C crosses 0.5, and is therefore closer to 0.5 for a longer period of time.

CONCLUSIONS

We have measured and modeled the on-sun performance of GaInP/GaAs tandem cells under direct illumination for concentrator applications. This study gives direct support for the use of the Low AOD spectrum to design cells for maximum daily energy and midday power. A similar "Clear Sky" standard spectrum, and even the AM 1.5G spectrum will also work quite well. The AM 1.5D spectrum is a poor choice, unless maximizing morning and/or evening power production is a priority. The similarity between the observed and modeled performance validates the use of modeling for design of concentrator cells.

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14. ABSTRACT *(Maximum 200 Words)*

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