# Outdoor Testing of GaInP$_2$/GaAs Tandem Cells with Top Cell Thickness Varied

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## ABSTRACT

In this study, we measure the performance of GaInP$_2$/GaAs tandem cells under direct beam sunlight outdoors in order to quantify their sensitivity to both spectral variation and GaInP$_2$ top-cell thickness. A set of cells with five different top-cell thicknesses was 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 either the ASTM G-173 direct (G-173D) spectrum or the "air mass 1.5 global" (AM1.5G) spectrum perform the best, and (2) cells can be characterized indoors and modeled using outdoor spectra with the same result. These results are equally valid for GaInP$_2$/GaAs/Ge triple-junction cells.

## 1. 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 cell. Because the solar spectrum changes throughout the day, different top-cell thicknesses ($t_{top}$s) are optimal for different times of the day. This raises two questions: "What $t_{top}$ is best for my application?" and "How critical is that choice?" This study is intended to aid in that selection.

In the first half of this paper, we will compare 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, GaInP$_2$/GaAs tandem cells designed for either the AM1.5G [1] or the ASTM G-173 direct (G-173D) [2] spectrum perform the best. The G-173D spectrum was recently developed to replace the ASTM G159 "AM1.5D" standard spectrum, which differed significantly from the direct spectra observed at locations suitable for concentrating photovoltaics. Within the context of our study, the G-173D spectrum is virtually identical to a previously proposed Low AOD (Aerosol-Optical Depth) spectrum [3]. The results presented in this paper agree well with a previous theoretical study [4], 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, using measured outdoor direct spectra as an input. 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 for a clear, high altitude site in the southwestern United States.

## 2. Experimental Details

To give some background, the model results in Fig. 1 show how performance should vary with $t_{top}$ under several standard reference spectra [1-3,5]. 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 $t_{top}$ values for these cells are shown along the bottom axis. Cell A has the thinnest $t_{top}$ and is well suited to "blue-rich"
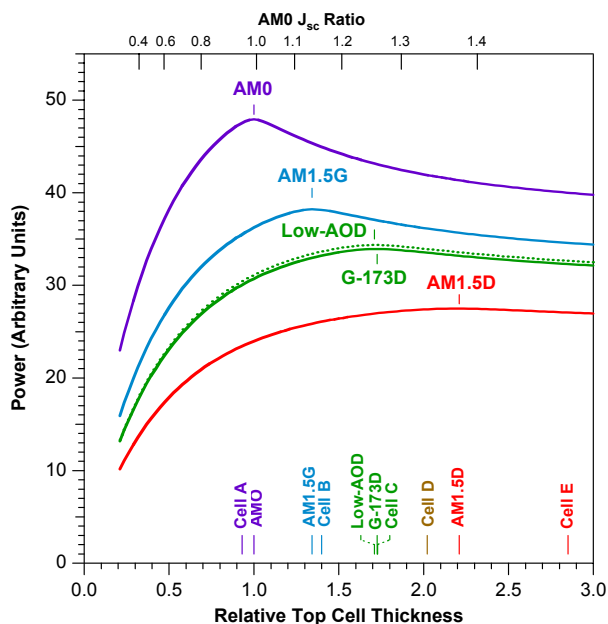


Figure 1. Calculated power produced by a GaInP/GaAs/Ge triple-junction cell as a function of $t_{top}$ for AM0, AM1.5 Global, *old* AM1.5 Direct (G159), and G-173 Direct standard reference spectra. Results for the Low-AOD spectrum are shown for comparison. Relative $t_{top}$ values are shown, normalized to the optimal AM0 $t_{top}$. Although the power produced by a GaInP/GaAs tandem cell will be less than for a triple-junction cell, the optimal $t_{top}$ for any given spectrum will not change. Approximate $t_{top}$ values for cells A - E are indicated.

space applications (i.e. AM0 [5]). 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. Cell B is nearly optimal for the AM1.5G spectrum, whereas Cell C is closely matched to the G-173D spectrum. As a gauge of experimental error, two cells were grown with the median $t_{top}$ (C1 and C2).

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. [6], with a 5° field of view. To simplify the interpretation of our results, 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.

## 3. 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 outperformed 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.

## 4. Model Details

To better understand the experimental results, we applied a simple device model (based on Ref. [7]) 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.
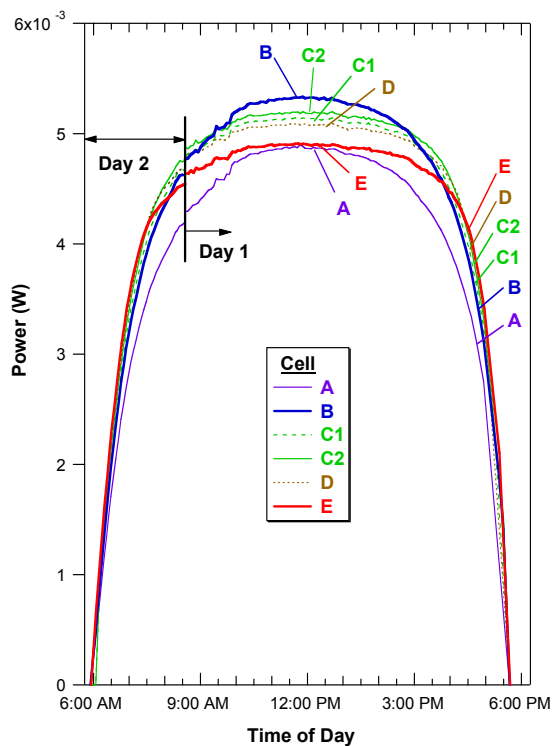


Figure 2. Measured powers for cells A - E on Sept. 23-24, 2004, at NREL, in Golden, Colorado. Because no morning data were taken the first day, data from the morning of the second day are substituted. Cells are labeled in the order of performance midday and during the evening. The cell area for each cell is 0.253 cm².

| Cell | $t_{top}$ (relative) | Energy (Wh) | Relative Energy (%) | Design Spectrum (approx.) |
|------|------|------|------|------|
| A | 0.93 | 0.4626 | 89.51 | AM0 |
| B | 1.40 | 0.5140 | 99.46 | AM1.5G |
| C1 | 1.73 | 0.5082 | 98.34 | G-173D |
| C2 | 1.73 | 0.5168 | 100.00 | G-173D |
| 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-cm² cell over the test day shown in Fig. 1. The $t_{top}$ values are approximate.

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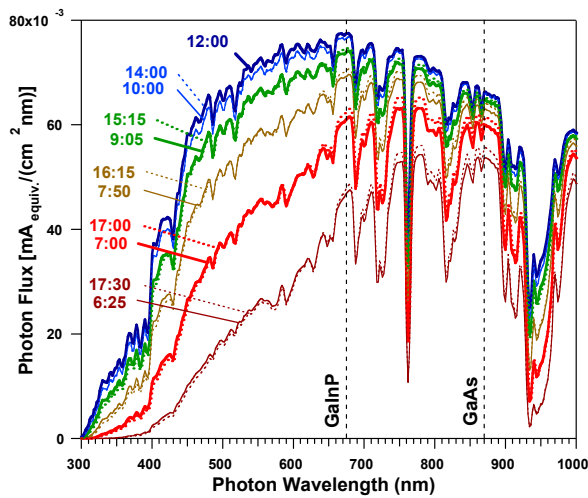
Figure 3. Measured direct spectra labeled by time of day during the test day. The photon flux is expressed as mA equivalent for 100 percent conversion of photons to photocurrent, per cm$^2$ area and nm of wavelength. The GaAs and GaInP band gaps are indicated with vertical dashed lines. Morning spectra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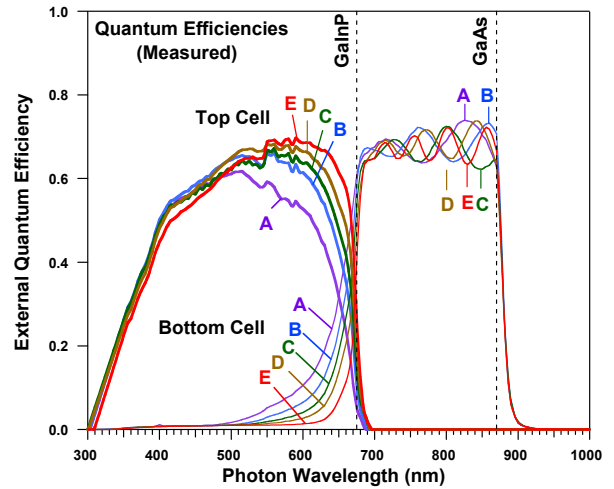


Figure 4. Measured external quantum efficiencies for the top and bottom cells. A small non-physical sub-band-gap top cell response was removed by smoothly setting the top cell QE to zero for wavelengths greater than ~700 nm. Cell C is represented by C2. (Cell C1 data is not shown.)

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. [8].

Above the GaInP band gap, both the top- and bottom-cell QEs change with $t_{top}$. As $t_{top}$ 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.

## 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)] for each cell, at each time of day. These $J_{sc}$ values were then fed into standard diode equations to generate decoupled top- and bottom-cell I-V curves. Tandem-cell I-V curves were then constructed by adding top- and bottom-cell voltages with the top- and bottom-cell currents matched. The resulting power at the maximum-power point for each tandem-cell I-V curve is plotted versus time of day in Fig. 5. These results and the experimental results (Fig. 2) display the same trends with respect to $t_{top}$ and time of day.
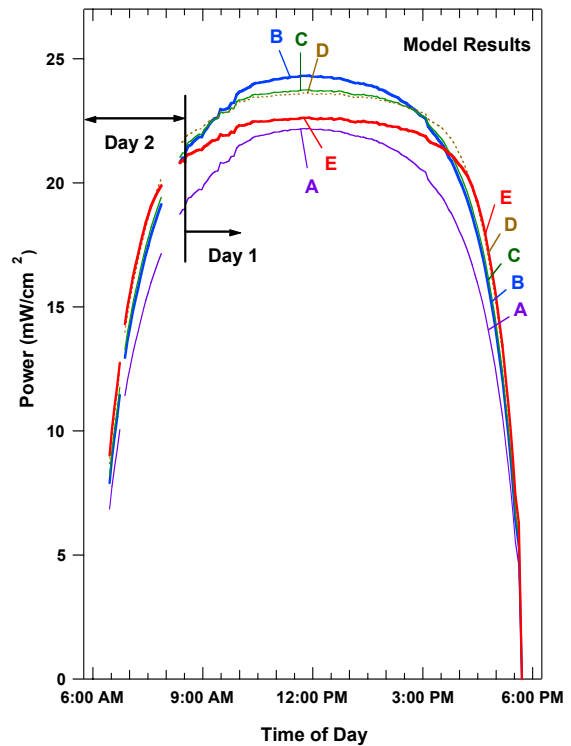


Figure 5. Model results for the test day shown in Fig. 2. Gaps in the curves occur whenever the direct spectra was not recorded.

Therefore, within the context of this paper, this sort of modeling can serve as a relatively quick and convenient supplement or alternative to outdoor measurements.

Modeling can also be used to illustrate how current matching changes throughout the day, directly affecting
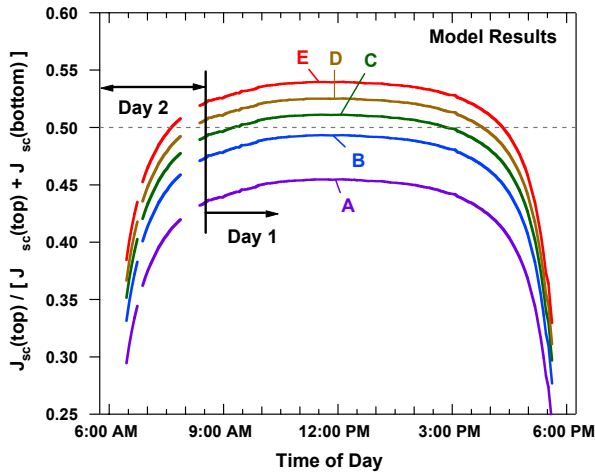
Figure 6. Modeled decoupled short-circuit currents (plotted as a ratio) during the test day. The best power production is for a current-matched cell with a ratio of 0.5, which corresponds to $J_{sc}(top) = J_{sc}(bottom)$.

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. For cells with high fill factors, 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.

### 6. Cell Temperature

Before concluding, the effect of cell temperature should be mentioned. In order to focus specifically on spectral effects, cells in this study were held at a constant temperature. However, cells in a concentrator system are unlikely to operate at constant temperature. The exact temperature will depend upon the cooling method, the ambient temperature and the solar irradiance. As temperature increases, every cell's band gap will drop, allowing the top cell to absorb a proportionally larger portion of the incident spectrum. Therefore, if cells are to be operated at elevated temperatures, $t_{top}$ should be thinned accordingly. An illustration of this effect can be found in Fig. 4 of Ref. [4].

### 7. Conclusions

We have measured and modeled the outdoor performance of GaInP/GaAs tandem cells under direct illumination for concentrator applications. This study gives direct support for the use of the ASTM G-173 direct spectrum to design cells for maximum daily energy and midday power. A similar "Low AOD" spectrum, and even the AM1.5G spectrum will also work quite well. The old

G159 "AM1.5D" 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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