Criteria for the Design of GaInP/GaAs/Ge Triple-Junction Cells to Optimize Their Performance

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CRITERIA FOR THE DESIGN OF GaInP/GaAs/Ge TRIPLE-JUNCTION CELLS TO OPTIMIZE THEIR PERFORMANCE OUTDOORS

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ABSTRACT

This paper investigates which reference spectrum should be used to design GaInP/GaAs/Ge triple-junction cells (at 300 K) in order to optimize their performance outdoors (at elevated temperatures). The outdoor performance is simulated using direct spectra from the recently proposed Module Energy Rating Procedure. We find that triple-junction cells designed for AM1.5D, low-AOD and AM1.5G standard spectra at 300 K all work well for maximizing daily energy production at elevated temperatures. AM1.5G cells are the best choice for midday power production, whereas AM1.5D cells are the best choice for power production during the morning and evening. Performance of cells optimized for a newly proposed Low-AOD spectrum is intermediate between these two extremes.

BACKGROUND

To begin, it is important to understand how the top cell thickness affects the performance of GaInP/GaAs/Ge triple-junction cells. At one extreme, a very thin GaInP top cell will produce almost no photocurrent, so the entire triple-junction cell will be photocurrent-limited by the top cell. At the other extreme, a triple-junction cell with a very thick top cell will generally be photocurrent-limited by the middle (GaAs) cell. Since a triple-junction cell must be current-matched for optimal performance, the optimal top cell thickness lies between these two extremes, and will depend upon the incident spectrum. This last point is very important, and is the focus of this paper.

As an example, in Figure 1 we use the methods of Reference [6] to simulate the power produced by a triple-junction cell as a function of top cell thickness ($t_{top}$) under
illumination by four standard spectra at 300 K. The peak of each curve has been labeled and the corresponding ttop has been indicated on the horizontal axis. For ease of comparison, these same four values of ttop are also labeled on subsequent plots. Of the four spectra, the AM0 spectrum is most heavily weighted toward photons with an energy greater than the GaInP top cell’s band gap. Therefore, the optimal ttop for AM0 is the thinnest. Because the other spectra contain fractionally less of this short-wavelength light, the top cells must be thicker for optimal performance.

Notice that ttop is expressed as a relative thickness, stated as a fraction of the optimal top cell thickness for AM0 illumination. Since the actual top cell thickness depends upon specific cell design choices, it is not a good basis of comparison between cells outside the confines of a self-contained self-consistent study. For comparison with triple-junction cells outside this study, the top axis shows the Jsc ratio (Jsc,GaInP/Jsc,GaAs) under AM0 illumination is shown along the top axis (also shown in subsequent figures).

RESULTS

In Figure 2 we use solar spectra from the Module Energy Rating Procedure [3] to simulate the power produced by a triple-junction cell under 500x illumination as a function of ttop and time of day for a standard “hot sunny day”. The ttop corresponding to the maximum of each curve is indicated just above the bottom axis in this and subsequent figures. The line used to label each curve is positioned at the curve maximum. The cell temperature for each hour is:

\[ T_\text{cell, hour} = T_\text{ambient, hour} + (40 °C)(\text{Irradiance}_\text{hour}/800 \text{ Watts}) \]

The ttop giving the maximum power at noon (hour 12) and the maximum daily energy have been labeled just above the bottom axis.
Table 1: Performance of cells designed for condition B and used for condition A (at 500x concentration). For each of the eight cells, the corresponding decoupled Jsc ratio and ttop are given (leftmost two columns). The HS Day, Nice Day and CS Day cells were optimized for maximum daily energy. The other four cells were optimized for maximum power under the given spectra. The cell temperature is 300 K for the AM0, AM1.5G and AM1.5D cells. The cell temperature for the other cells is given by:

\[ T_{cell,hour} = T_{ambient,hour} + (40 °C)(Irradiance_{hour}/800 Watts). \]

This gives a temperature of 85 °C for the HS Day at Noon cell, and a variable temperature for the remaining three cells.

<table>
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<td>1.00</td>
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<td>93.7</td>
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<td>99.4</td>
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<tr>
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<td>Hot Sunny Day</td>
<td>98.9</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
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</tr>
<tr>
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<td>100.0</td>
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<tr>
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<td>97.6</td>
<td>97.9</td>
<td>98.2</td>
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</table>

sunny day\(^\text{°}\). Elevated cell temperature during operation is simulated by the formula \([8]\) given in the figure caption, using the hourly ambient temperatures given for the standard days in Reference [3]. Notice that for each hour of the day the maximum shifts to a different value of \(t_{top}\). This is directly related to changes in the spectral distribution of the incident spectrum (and to changes in cell temperature). If a given spectrum contains relatively more high-energy photons (\(\nu > E_{g,GaInP}\)), \(t_{top}\) will be thinner. For most hours of the day the maximum of each curve (and therefore the optimal \(t_{top}\)) falls between 1.3 and 1.6. Notice that an AM1.5G cell lies within this range and will therefore perform well throughout most of the day. An AM1.5D cell will be optimal only for the 8AM (hour 8) and 6PM (hour 18) spectra, and an AM0 cell is never optimal.

If the power curves shown in Figure 2 are summed to give the total energy produced by a given cell over the course of an entire day, the maximum daily energy (MDE) will be produced by a cell with a \(t_{top}\) of 1.47. Not surprisingly, this value gives nearly optimal power production during the peak power-producing hours of the day.

These trends can also be seen in Figure 3. Here we use the curves of Figure 2 to plot the power output of seven different triple-junction cells as a function of time of day during a standard hot sunny day. The uppermost curve is for a fictitious triple-junction cell for which \(t_{top}\) can be varied throughout the day to give optimal power production. The remaining six curves are for triple-junction cells with a fixed \(t_{top}\) designed for specific conditions. The AM0, AM1.5G, Low-AOD and AM1.5D cells are designed for maximum power production under their respective spectra at 300 K. The "noon" cell is optimized for power production at noon (at an elevated temperature). Finally, the "MDE" cell produces the maximum daily energy (at a varying elevated temperature). The curves are labeled in decreasing order of power produced at noon and at 6:00 PM. Although unlabelled, the arrangement of curves is the same for the morning as it is for the evening.

The Noon, AM1.5G and MDE cells all produce near-optimal power during the middle peak-power production portion of the day. In Figure 3 they are very close to the upper-limit given by the fictitious variable-top-cell curve during the middle portion of the day. Because the \(t_{top}\)s for these three cells are between 1.3 and 1.6, they lie near the maxima of the majority of the highest curves in Figure 2. However, performance during the morning and evening hours is compromised. At the other thickness extreme, the AM1.5D cell performs best during the morning and evening, and poorly during the middle of the day. This can be verified in Figure 2, where the "AM1.5D" \(t_{top}\) lies near curve maxima at 8 AM and 6 PM. The Low-AOD cell lies between these two extremes, and the AM0 cell never performs well because its \(t_{top}\) is always too small.

All of the curves shown in Figures 2 and 3 are for triple-junction cell performance simulated during a standard hot sunny day. But for most applications, simply discussing performance during a single day is not adequate. In addition, one must ask how a cell optimized for this one hot sunny day would perform on different days throughout the year, during which the incident spectra will be different. A comparison of this sort is shown in Table 1. The numbers in the table are the percentage of optimal performance, defined as:

\[
\frac{\text{Performance if designed for B and used for A}}{\text{Performance if designed for A and used for A}} \times 100\% ,
\]

where "performance" is defined in terms of energy for the three standard days, and power for the "hot sunny day at noon" spectrum.

For daily energy production, all cells except for the AM0 cell perform quite well. The performance losses are all ≤3%. However, if midday power production is also considered, cells with thinner \(t_{tops}\) perform noticeably better. If both midday power and total daily energy are both important, the hot sunny day cell performs the best, closely followed by the AM1.5G cell.

Finally, the effect of temperature should be considered. As cell temperature is increased, all three band gaps decrease, so the top (GaInP) cell can absorb a proportionally larger portion of the incident spectrum. Therefore, as the cell temperature is increased, \(t_{top}\) should be decreased for optimal performance.
This temperature effect can be clearly seen in Figure 4, where cell performance is plotted for three different values of the temperature coefficient $m$ (see figure caption). For $m = 0^\circ C$, the cell operating temperature will be near room temperature, so designing for a Low-AOD spectrum at 300 K works quite well. This is easy to understand, since both the design spectrum and the design temperature were close to the operating conditions.

At very high operating temperatures ($m = 80^\circ C$), a cell designed for an AM1.5G spectrum at 300 K will work the best. In this case, both the design temperature and spectrum were inaccurate (different from the actual operating conditions). However, raising the cell temperature and making the spectrum more blue-rich affect the cell design in the same way (the optimal $t_{top}$ is thinner), so the two errors cancel each other out. Of course, the most accurate and least confusing way to simulate cell performance (and design cells) would be to use the most accurate spectrum (Low-AOD) and a representative elevated cell temperature (not 300 K).

A final subtlety is that the performance curves in Fig. 4 are asymmetric. When it comes to uncertainties in the operating temperature, it is better to make the top cell a little too thick instead of a little too thin.

**CONCLUSIONS**

Because spectral variations can have a dramatic effect on the performance of triple-junction solar cells, the choice of design spectrum requires some careful consideration. In this study we find that triple-junction cells designed for AM1.5D, Low-AOD and AM1.5G standard spectra at 300 K all work well for maximizing daily energy production at elevated temperatures. AM1.5G cells are the best choice for midday power production, whereas AM1.5D cells are the best choice during the morning and evening. Low-AOD cell performance is intermediate between these two extremes.

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**REFERENCES**


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