CONCENTRATOR TRIPLE-JUNCTION SOLAR CELLS AND RECEIVERS IN POINT FOCUS- AND DENSE ARRAY MODULES

R. A. Sherif, R. R. King, H. L. Cotal, D.C. Law, C.M. Fetzer, K. Edmondson, G. S. Glenn, G. Kinsey, D. Krut, and N.H. Karam
Spectrolab, Inc., 12500 Gladstone Ave., Sylmar, CA 91342 USA

ABSTRACT: Multijunction III-V solar cells have been sought for use in concentrator modules as they enable electricity production at lower $/kWh. With efficiencies approaching 40% at concentrations of a few hundred suns, innovative concepts in concentrating the light on the solar cells have emerged. Some concentrator modules utilize Fresnel lens or individual reflective optics to focus the light on individual cell assemblies. Other concentrator modules utilize reflective optics to focus the light on a dense array of solar cells. Triple junction GaInP/GaInAs/Ge solar cells have been used with both approaches. This paper discusses the status of the concentrator systems and the triple junction solar cells used. It describes the different tradeoff issues related to the cost, performance and reliability.

1 INTRODUCTION

The use of concentrators, where the more expensive semiconductor is replaced with less expensive optics and other common materials, has been back on the forefront again as a feasible option to reduce the cost of solar electricity. The emergence of III-V multijunction (MJ) solar cells is credited with this renewed interest in solar concentration. Today, the world-record conversion efficiency of the state-of-the-art triple junction GaInP/GaInAs/Ge solar cell is 39.0% at concentration of about 200 suns. Innovative concepts to concentrate the light on the solar cells and extract the heat away from them have come to play, as the need for a total system solution is needed to achieve overall cost targets. There are several tradeoffs in any concentrator system. They involve the concentration level, the type of optics (reflective vs. refractive), whether a secondary optical element is to be used, active vs. passive cooling, etc. Typical concentrator systems of today are going after a 500X concentration level, which is believed to offer a sweet spot for the solar cells and for the overall system economics. with MJ cells have been around 500 suns; however, the push for hig . At this concentration level, 1 cm^2 of cell area produces the same electricity as 500 cm^2 would without concentration. The replacement of semiconductor area by cheaper, more conventional materials, e.g., optics, steel, and aluminum, reduces the cost per collector area, even after accounting for the tracking and cooling costs [2].

The choice of which concentration level to use on any solar cell, be it silicon or multijunction, is dictated mainly by the economics of the system. There are generally 4-concentration regimes in a Concentrating Photovoltaic (CPV) module, depending on the concentration level, as shown in Fig. 1.

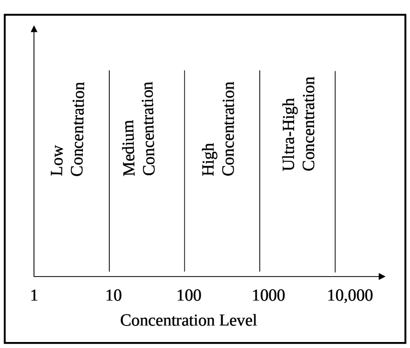

Figure 1. Concentration Regimes with MJ Solar Cells

At concentration under 10X, typical flat plate silicon cells of 15% efficiency can be used with little modifications to the grid lines [3]. The tracking accuracy can be very crude in this concentration regime, with no special cooling requirements to be fulfilled. As the concentration level increases, tracking and thermal management issues become more critical. However, MJ cells cannot still be economically feasible until the High Concentration regime (defined as concentration in the hundreds of suns) is reached. This is simply due to the fact that the MJ cell cost at production of 10s of MW per year is projected to be in the $5-9 per cm^2 [1]. In order for the MJ cell to be under $0.5 per Watt, concentration needs to be in the hundreds of suns. As the concentration level enters the Ultra-High regime (defined as concentration above 1000 suns), issues of thermal management push the cell size to a few square millimeters, thus increasing the requirements for the tracking accuracy. Further, issues of tunnel junction stability, driven by high current densities, become critical. It is interesting to note that the so-called Medium Concentration regime (above 10X but under 100X) is of no practical interest, as the increased output of the cells is not sufficient to offset the added complexity and cost of tracking and thermal management

This paper deals with the Ultra-High concentration regime. It aims to address the feasibility of having MJ cells operating in concentrations above 1000 suns.

2 THERMAL ANALYSIS

When it comes to concentration level in the Ultra-High Concentration regime, heat removal becomes one of the key parameters that limit the choice of the cell size. In this regard, we note that when it comes to removing heat from a solar cell, it is important to consider not just the power density (which corresponds to the concentration level) but also the magnitude of the power itself. Therefore, at concentration levels above 1000X, which correspond to power densities of 700 W/cm^2, it is important to keep the cell size as small as possible. Figure 2 shows the results of a 3-dimensional finite element model for solar cells of different sizes subjected to concentration levels of 1000-5000X.

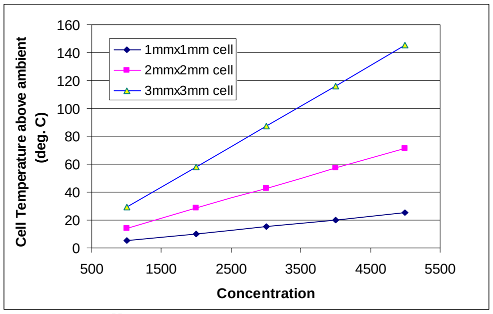

Figure 2. Cell Temperature Projections in 1000-5000X

In this model, we assumed the solar cell to be soldered directly to a copper heat spreader. Direct soldering of the cells to Cu is usually not practiced for larger cells (e.g., $1cm^2$) since the coefficient of thermal expansion (CTE) of Cu is much higher than that of the MJ cell. Under repeated temperature cycling, large expansion mismatch can lead to breakage of the cell and/or the solder joint between the cell and the heat spreader, leading to loss of cooling and thermal runaway.

In this model, the heat spreader has dimensions of 5cm x 5cm and its thickness is 2mm. Heat removal from the back of the heat spreader occurs by natural convection (i.e., passive cooling) with the heat transfer coefficient assumed to be 100 W/m^2-deg C, which is typical of natural heat convection. From the curves in Fig. 2, it is clear why the cell size should be limited to < $4mm^2$ under concentration above 3000 suns.

3 PERFORMANCE OPTIMIZATION

We will focus our attention on performance optimization of the current state-of-the-art GaInP/GaInAs/Ge triple-junction cells. We will consider cell sizes that are $1\text{-}4mm^2$, as shown by the results of the thermal analysis. We start with the grid line optimization, which entails computing a number of loss components that affect the power output of the cell. These include the amount of metal deposited on the front surface, its obscuration (or shadowing), sheet resistance across the plane of the front face of the semiconductor, I^2R heating through gridlines and busbars, contact resistance between the front metal, and the semiconductor and tunnel junction losses. The procedure of optimizing a concentrator cell has been discussed in detail in [4]. Figure 3 shows a graph of the relative power loss of a $1mm^2$ triple junction concentrator solar cell for 1000, 3000 and 5000 suns for a $1mm^2$ cell at a given sheet- and contact resistance.

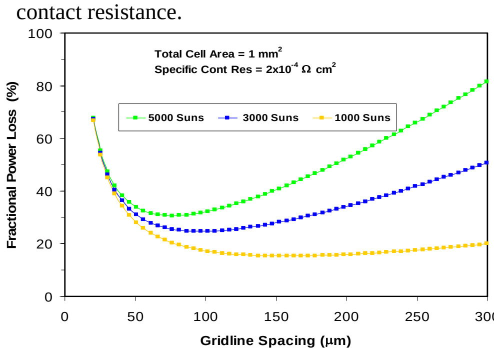

Figure 3. Grid Line Optimization for a $1mm^2$ 3J Cell in the Ultra-High Concentration Regime

The data in Fig. 3 suggests that the gridline spacing should be about 200 microns for 1000 suns. The cell performance is fairly insensitive for gridline spacing between 150-300 microns. At concentration of 3000 suns, the optimum grid spacing is about 100 microns, and the dependence on the gridline spaing becomes stronger. At 5000 suns, the optimum spacing drops to about 75 microns and any slight deviation from that causes a larger drop in cell performance.

Additional optimization of a ceoncentrator cell in the Ultra-HighConcentration regime involves optimizing the sheet resistance and the front metal contact resistance. Figures 4 and 5 show the impact of the sheet resistance and contact resistance (respecitvely) on the fractional power loss at concentration of 5000X.

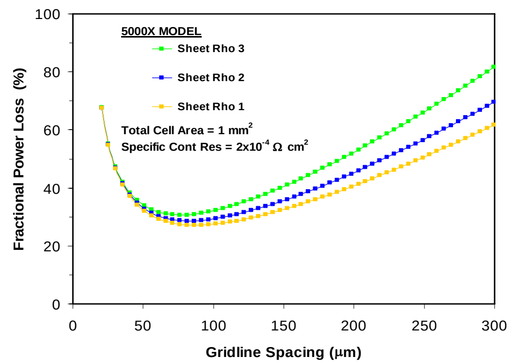

Figure 4. Impact of Sheet Resistance on Performance for $1mm^2$ cell at 5000X

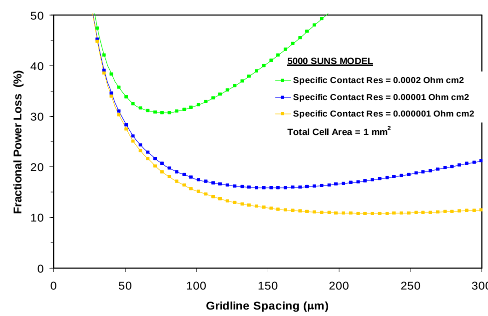

Figure 5. Impact of Front Metal Contat Resistance on erformance for $1mm^2$ cell at 5000X

The data in Fig. 4 shows that at the optimum gridline spacing, the impact of the sheet resistance on the fractional pwoer loss is minimal. However, if the gridlines were designed for optimum operation under, say, 1000X, and then the cell was to operate under 5000X the impact of the sheet resistance starts to become more significant. The data in Fig. 5 suggests that more effort should be put on reducing the contact resistance, as the impact of lower contact resistance on fractional power loss is very large.

Tunnel Junction Stability

The solar cell structure is grown in the Metal Organic Vapor Phase Epitaxy (MOVPE) reactors. The epitaxial layers grown in the MOVPE reactors must balance the peak current output from each electrically active junction. Each pair of junctions is bridged by a tunnel-junction allowing current to flow with ease between the electrically active junctions. The primary characteristic of a tunnel junction is its peak tunneling current. This is the maximum current density for which a tunnel junction operates without severely hindering cell performance. Current flow between each pair of electrically active junctions is limited by the peak current density (J_p) of the tunnel junction. Figure 6 illustrates the tunnel junction characteristics in the present tunnel junction used in the triple junction structure.

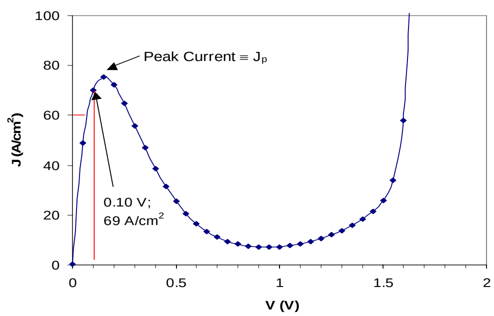

Figure 6. Tunnel Junction Characteristics of a 3J Cell

For a concentrator cell operating at 5000 suns, the current density at maximum power (J_{mp}) for this cell design is 69 A/cm^2. In Fig. 4, the voltage drop that corresponds to this J_{mp} is about 0.10 V, and would be manifested in the form of power loss in the cell performance due to this component. Although the voltage drop is somewhat low, its J_p is not high enough as J_p should be 2- but preferably 3-times higher than J_{mp} of 69 A/cm^2. Since variations in the growth of tunnel junctions can occur, these factors give a margin of safety to compensate for such variations. Since J_p is low, this particular tunnel junction would not be suitable for a concentrator cell at 5000 suns. This was confirmed experimentally by studies done with concentrated light coming out of a fiber shining light on smaller areas of the cell. Occasional tunnel junction failures were reported at concentration levels slightly above 2200 suns. [5].

It is clear that we need to define a tunnel junction that has peak tunneling current of at least 140 A/cm^2 (but preferably higher than 200 A/cm^2). The peak tunneling current is dependent on the band gap (E_g) of the semiconductor: the lower the E_g, the higher the J_p. The choice of E_g, however, is one where E_g should be low enough to allow for high J_p (and low voltage drops) but high enough to reduce light absorption in the tunnel junction. The plot in Fig. 6 is representative of a tunnel junction with E_g of 1.9 to 2.0 eV. Some tunnel junctions that fall in the category of high J_p and low E_g could be the AlGaAs/InGaAlP, AlGaAs/GaInP and AlGaAs/GaAs ternary and quarternary systems. By proper adjustment of the Aluminum, Gallium and Indium compositions, the desired tunnel junctions with lower E_g can be developed with J_p above 200 A/cm^2.

4 OPTIMUM CELL AREA

Previous discussions focused on individual cells. The smaller the cells, the easier the heat dissipation is and the smaller the I^2R losses are. In smaller cells, however, the ratio of the bus bar to the active cell area is larger; hence, on a wafer level, smaller cells will correspond to larger loss of wafer active area (and hence lower power). Since the ultimate objective of any concentrating PV system is to reduce the cost of electricity generation ($/kWh), the wafer power output must be taken into account when deciding on the optimum cell area.

A 10cm diameter Ge wafer is used for growing epitaxial layers to form the terrestrial concentrator structure. If we eliminate the unusable wafer area, then a 1mm^2 aperture area cell will produce 6,219 cells per wafer, whereas a 4mm^2 aperture area cell will produce 1,613 cells per wafer (with a 60 micron wide busbar).

At 5000 suns under Standard Test Condition (STC) of 25 deg. C cell operation, the following power is achieved from each cell and wafer.

Standard Test Condition

Power of 1mm^2 cell = (I_{mp} = 0.52A) x (V_{mp} = 2.68V) = 1.4 Watts/cell. Power of a 10-cm wafer = 1.4 (W/cell) x 6,219 (cells/wafer) = 8.67 kW/wafer

Power of 4mm^2 cell = (I_{mp} = 2.22A) x (V_{mp} = 2.68V) = 5.95 Watts/cell. Power of a 10-cm wafer = 5.95 (W/cell) x 1,613 (cells/wafer) = 9.60 kW/wafer

This clearly favors the use of the larger cell, as it shows abou 11% increase in the wafer output power. In actuality, however, the smaller cell will operate at lower temperature, as was shown in Fig. 2. Inclusion of the temperature effects (and assuming 25 deg. C ambient), we obtain the following.

Real Temperature Test Condition

Power of 1mm^2 cell = (I_{mp} = 0.52A) x (V_{mp} = 2.59V) = 1.35 Watts/cell. Power of a 10-cm wafer = 1.35 (W/cell) x 6,219 (cells/wafer) = 8.38 kW/wafer

Power of 4mm^2 cell = (I_{mp} = 2.22A) x (V_{mp} = 2.35V) = 5.22 Watts/cell. Power of a 10-cm wafer = 5.22 (W/cell) x 1,613 (cells/wafer) = 8.42 kW/wafer

In other words, the fact that the smaller cells will operate at lower temperature made the use of either cell almost equivalent in terms of total wafer power.

5 EXPERIMENTAL RESULTS

Concentrator solar cells of 1mm^2 and 4mm^2 aperture areas were fabricated at Spectrolab and were tested under ultra-high concentration levels. The cells were tested on the wafer level using the High Intensity Pulsed Solar Simulator (HIPSS). The cells have gridlines that are 200 microns apart. In other words, the cells were optimized for 1000X.

Figure 7 shows the spectral response measurements of the cells. Figure 8 shows the HIPSS data obtained for the 1mm^2 cell, whereas Fig. 9 provides the HIPSS data for the 4mm^2 cell. The data in Table 1 provides a summary of the I-V parameters of the 1mm^2 cell, whereas the data in Table 2 is for the 4mm^2 cell. The data show the efficiency above 33% at 1000X before it drops at higher concentrations due to the drop in the fill factor caused by the series losses. This is consistent with the performance modeling projections of optimum gridline spacing for these cells.

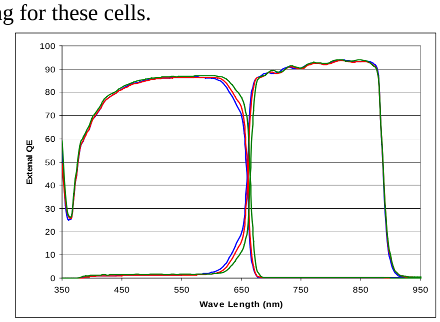

Figure 7. External Quantum Efficiency for the 3J Cells used in this study

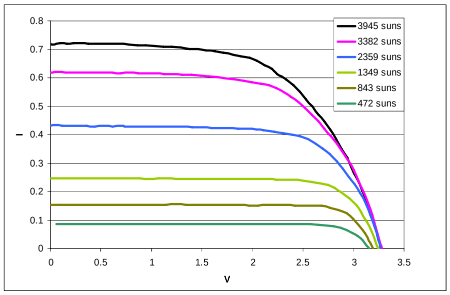

Figure 8. HIPSS Data on the $1mm^2$ Cell, at concentrations of 400 suns up to 4000 suns

Concentration	Voc	FF	Power	Eff.
472 suns	3.153	0.819	0.223W	34.8%
843	3.190	0.814	0.401	34.99%
1349	3.245	0.764	0.613	33.43%
2359	3.267	0.695	0.982	30.59%
3382	3.278	0.625	1.268	27.59%
3945	3.271	0.585	1.383	25.78%

Table 1. HIPSS Data for the $1mm^2$ Cell

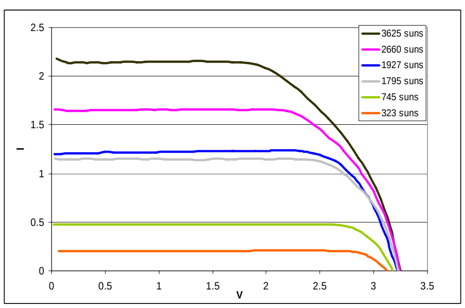

Figure 9. HIPSS Data on the $4mm^2$ Cell, at concentrations of 320 suns up 3620 suns

Concentration	Voc	FF	Power	Eff.
323 suns	3.127	0.854	0.553	35.99%
745	3.178	0.828	1.259	35.49%
1795	3.230	0.759	2.825	33.07%
1927	3.228	0.750	2.995	32.64%
2660	3.245	0.667	3.697	29.19%
3625	3.248	0.567	4.281	24.81%

Table 2. HIPSS Data for the 2mm x 2mm Cell

6. COST PROJECTIONS

A $1mm^2$ aperture area cell will operate at less than 10 deg. C above ambient at 1000X concentration, and will have an efficiency of 33%. Under these conditions, the cell cost projection is given in Fig. 10.

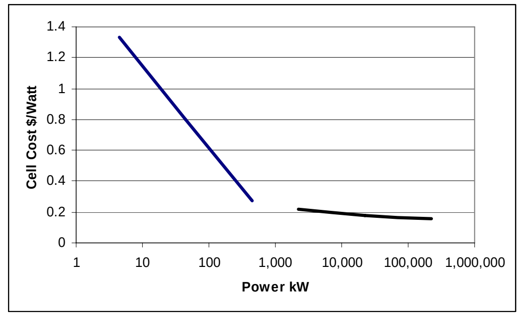

Figure 10. Cost Projections for a $1mm^2$ Triple-Junction

7. CONCLUSIONS

The performance and economics of Ultra-High Concentration modules with MJ cells seem to be quite favorable. Passive cooling of cells < $4mm^2$ is possible with direct bonding of the cells to the heat sink, with maximum temperature rise below 30 deg. C at 2000X for $4mm^2$ cells and less than 10 deg. C above ambient for $1mm^2$ cells at 1000X. Performance modeling and experimental data show that triple-junction cells have achieved over 33% at concentrations of 1000X. This translates to cell cost of under $0.2 per Watt in volumes above 1MW. Future work will focus on demonstrating the reliability of triple-junction cells in the Ultra-High Concentration regime in continuous outdoor tests.

This work was funded in part by the National Renewable Energy Laboratory under the High Performance PV Program Phase 1B.

REFERENCES

[1] R. Sherif et al., “The Path to 1GW of Concentrator Photovoltaics Using Multijunction Solar Cells,” Proceedings of the 21st IEEE Photovoltaic Specialists Conference, Florida 2005.
[2] R. Swanson, “The Promise of Concentrators,” Prog. Photovolt. Res. Appl. Vol. 8, pp. 93-111, (2000).
[3] L. Fraas et al., “Efficienct Solar Photovoltaic Mirror Modules for Hlaf the Cost of Toda’s Planar Modules,” 3rd International Confrence of Solar Concentratotrs for the Generation of Electricity or Hydrogen, Scottsdale, AZ 2005.
[4] G. Kinsey et al, “Optimization of High-Concentration Multijunction Solar Cells,” 3rd International Conference on Solar Concentrators for the Genertion of Electricity or Hydrogen, Scootsdale, AZ 2005.
[5] J. Gordon et al., “Ultra-High Concentration Effects in Multijunction Solar Cells,” 3rd International Conference on Solar Concentrators for the Generation of Electricity or Hydrogen, Scottsdale, AZ 2005.