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Highly Efficient 32.3% Monolithic GaInP/GaAs/Ge Triple Junction Concentrator Solar Cells

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ABSTRACT

Results from Spectrolab-grown $Ga_{0.5}In_{0.5}P$/GaAs/Ge structures optimized for the AM1.5D spectrum are described along with progress toward developing next-generation multijunction solar cells for high concentration ratios (X). The structures were processed into small-area cells at NREL, and I-V tested vs. X. Many cells were tested, with the best cell eff. at 32.3% at 47X and 29% at 350X. The FF limited the devices above 60X. The V_{oc} vs. X showed its log-linear dependence on I_{sc} up to ~75X; a decrease in Voc at higher X is attributed to a bucking junction at the back of the Ge bottom cell. Based on recent cell improvements for space applications, multijunction cells appear to be ideal candidates for high eff., cost effective, PV concentrator systems.

1. Introduction

Recent performance improvements along with cost reductions carried out in the manufacture of $GaInP_2$/GaAs/Ge lattice-matched space solar cells has prompted Spectrolab to re-evaluate the application of this type of cell for use in terrestrial PV concentrator systems [1]. AM1.5D efficiencies of over 30% can now readily be achieved on triple-junction (3J) cells using device designs and high-yield production processes that are only marginally different from space cells. Since space and terrestrial multijunction cell technologies share the same manufacturing operations, cells with very low dollars per watt can be produced at modest manufacturing rates. This makes multijunction cells extremely attractive for achieving near-term reductions in PV generation costs.

$GaInP_2$/GaAs/Ge 3J cell layers were grown at Spectrolab in a production MOVPE reactor incorporating high-efficiency cell structures suitable for the high current densities encountered at concentration and the terrestrial spectrum. These epitaxially grown layers were then metallized and fabricated into concentrator cells by NREL for performance evaluation under an AM1.5D spectrum. A major difference in these devices compared to that of a space cell is a thicker, more heavily doped emitter to reduce sheet resistance across the surface that might otherwise cause significant performance losses at high concentration. Other layers of the cell were also adjusted to achieve current matching under an AM1.5D spectrum. Two device structures were modeled, and the grid design for both pace and terrestrial cells were optimized for each application.

2. Procedure

Light I-V measurements were performed at NREL on small area devices of 0.1039 cm^2 under their High Intensity Pulsed Solar Simulator (HIPSS) at 1 sun and under concentration. It should be pointed out that NREL has sent this cell to the Fraunhofer ISE in Freiburg, Germany for 1-sun measurements and performance verification. The short-circuit current (I_{sc}) and the maximum power agreed to within 0.2% of NREL's results. Further measurements for performance evaluation under concentration are underway by Fraunhofer ISE.

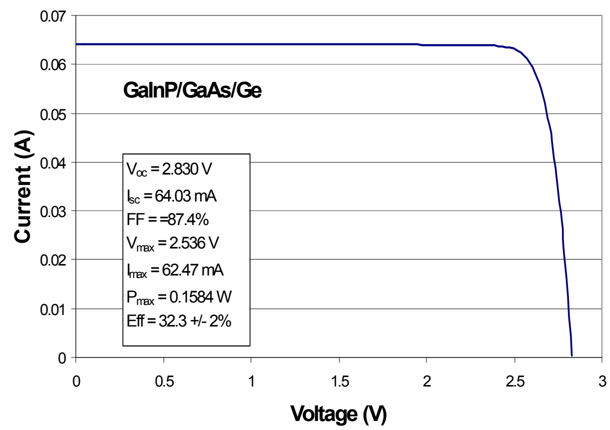

Figure 1: Light I-V characteristics of the best $GaInP_2$/GaAs/Ge TJ solar cell measured at AM1.5D and 47 suns by NREL.

3. Results and Discussion

Figure 1 shows a representative I-V curve for an early generation of small-area cells with the best cell yielding an efficiency of 32.3%. The other photovoltaic parameters of the cell are displayed in the figure. Many other cells were measured as a function of concentration level and gave efficiencies greater than 30%. All of their photovoltaic parameters were well-behaved with increasing concentration, and only the fill factor decreased.

In Fig. 2 is shown such a set of efficiency curves versus concentration for these initial cells, which were tested at NREL with remarkably high values. Just recently, other cells were processed and tested, and their device performance at concentrations greater than 200 suns was higher than the performance of the earlier cells. Figures 3 and 4 show their open-circuit voltage (V_{oc}) and fill factor characteristics for one of these high-concentration cells as a function of concentration ratios. The V_{oc} of the high-concentration 3J cells increased linearly on a logarithmic scale as expected from the sum of V_{oc} values for each subcell using the simple ideal-diode relation in forward bias::

$$V_{oc,3J} = V_{oc,c1} + V_{oc,c2} + V_{oc,c3} \approx \frac{kT}{q} \ln\left(\frac{J_{ph,c1} J_{ph,c2} J_{ph,c3}}{J_{o,c1} J_{o,c2} J_{o,c3}} \right)$$

where J_{ph} and J_o are the photogenerated and the saturation current density, respectively, for a given subcell, and c1, c2, and c3 designate subcells 1, 2, and 3 in the multijunction stack. As the incident intensity increases by a factor of ten, the J_{ph} in each subcell increases by a factor of 10 and the change in V_{oc} for the 3-junction solar cell is $(kT/q)\ln(10^3)$ = 177 mV/decade at 25°C for a diode-ideality factor of 1 for each subcell. For the high-concentration cells, the V_{oc} perform according to Eqn. (1) to concentration levels over 1000 suns, as shown in Fig. 3.

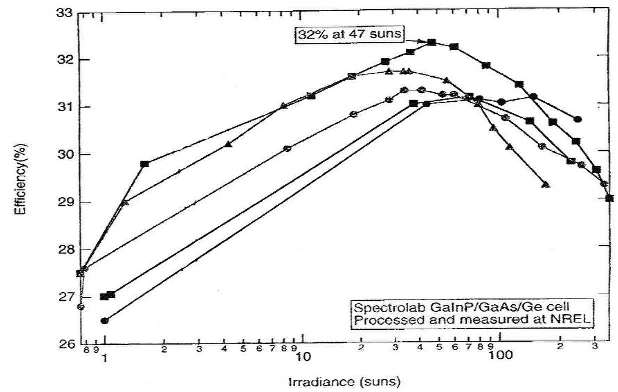

Figure 2: Spectrolab $GaInP_2$/GaAs/Ge TJ efficiencies versus concentration for 5 cells processed from the same wafer by NREL.

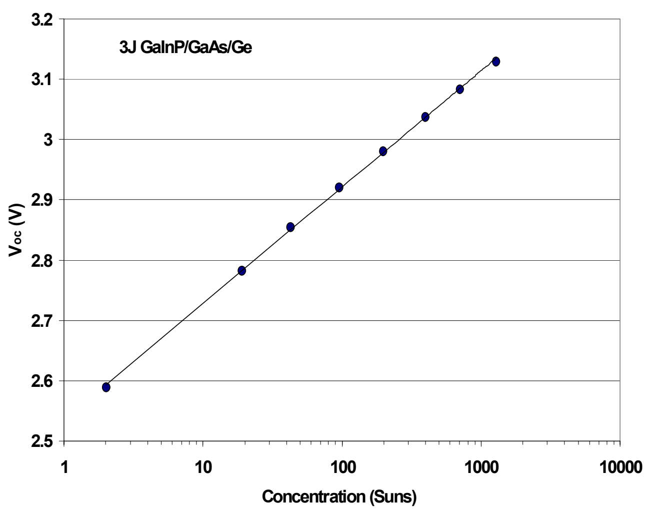

Figure 3: $GaInP_2$/GaAs/Ge TJ open-circuit voltage versus concentration ratio for high-concentration device (not shown in Fig. 1).

A wide-bandgap tunnel junction was used in between the GaInP top cell and the GaAs middle cell, in order to increase photogeneration in the middle cell [1,2]. The wider bandgap of the semiconductors used can increase the energy barrier for tunneling and thereby increase the resistance and lower the peak tunneling current for wide-bandgap tunnel junctions. However, a wide-E_g tunnel junction structure was chosen that has been found to be robust on thousands of cells at one-sun and at low concentration ratios, and which appears to have acceptably low voltage drops for over 500 suns.

Figure 4 shows more detailed features of the fill factor as a function of concentration for the cell of Fig. 3. The FF exhibits a maximum near 20 suns and then decrease steadily from 20 suns to over 1000 suns. The drop in FF is due to the increased role of the series resistance at higher concentrations.

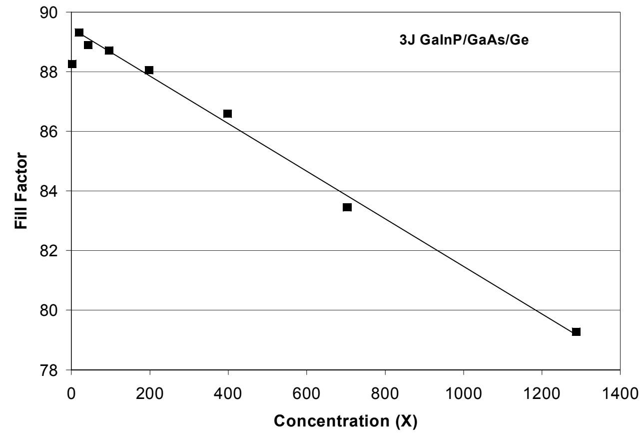

Figure 4: $GaInP_2$/GaAs/Ge TJ fill factor dependence on the concentration ratio.

Cell efficiencies as high as those shown in Fig. 2 present a remarkable message: in their present state, TJ cells can work effectively in a PV concentrator system and generate power in excess of 10 MWhr/yr for a system populated with only 500 cm^2 of cell aperture area! Even with the anomalous roll-off in V_{oc}, the efficiency was 29% at 350 suns, indicating that a concentrator system populated with such cells would yield a power output twice as high as that of commercial Si cells with 15% efficiency.

3. Conclusions

In conclusion, results from well-established, 3J space-based solar cell growth technology at Spectrolab showed efficiencies for the best device from an early generation of cells of 32.3% at AM1.5D. IV testing of improved cells is currently underway and will be presented in the paper. In the near future, low risk improvements will give rise to high-volume, industry-wide availability of cost effective cells above 30%. Several years from now, the opportunity will exist for cell costs to be less than $0.3/W with the introduction of improved 4-junction cell technology based on 1-eV materials.

ACKNOWLEDGEMENTS

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References

[1] N.H. Karam, R.R. King et al., "Recent Development in High-Efficiency GaInP/GaAs/Ge Dual- and Triple-Junction Solar Cells: Steps to Next Generation PV Cells," *Solar Energy Materials and Solar Cells,* 2000.

[2] D.J. Friedman et al., "Ge Concentrator Cells for III-V Multi-Junction Devices," submitted to this conference.