TRIPLE-JUNCTION SOLAR CELL EFFICIENCIES ABOVE 32%: THE PROMISE AND CHALLENGES OF THEIR APPLICATION IN HIGH-CONCENTRATION-RATIO PV SYSTEMS

H.L. Cotal, D.R. Lillington, J.H. Ermer, R.R. King, N.H. Karam
Spectrolab, Inc., 12500 Gladstone Ave., Sylmar, CA 91342 U.S.A

S.R. Kurtz, D.J. Friedman, J.M. Olson, J.S. Ward, A. Duda, K.A. Emery, and T. Moriarty
National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401, U.S.A

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 epitaxially-grown layers were processed into triple junction cells both at Spectrolab and NREL, and I-V tested vs. X. Cells were tested with efficiencies as high as 32.4% near 372 suns. The FF limited the performance with increasing X as a result of the increased role of the series resistance. The V_{oc} vs. X showed its log-linear dependence on I_{sc} over 1000 suns. Based on recent cell improvements for space applications, multijunction cells appear to be ideal candidates for high efficiency, cost effective, PV concentrator systems. Future development of new 1-eV materials for space cells, and further reduction in Ge wafer costs, promises to achieve cells with efficiencies > 40% that cost \$0.3/W or less at concentration levels between 300 to 500 suns.

INTRODUCTION

Concentrators have been regarded for many years as a way to reduce photovoltaic (PV) systems costs, since the cost of optics and a tracker are generally less than the cost of the solar cell itself. The increased complexity of tracking systems, however, together with the traditionally high cost of developing III-V cells, has hampered their widespread use of PV concentrator systems.

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 [1,2]. 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 cost per watt can be produced at modest manufacturing rates. This makes multijunction cells extremely attractive for achieving near-term reductions in PV generation costs. In addition, the leveraging of semiconductor manufacturing capacity afforded by the use of concentration allows a very rapid ramp up to achieve manufacturing capacity in excess of 150 MW per year using existing Spectrolab's manufacturing infrastructure.

Although the main body of the paper is based on results from 3J solar cells measured at high concentration ratios, a small portion will be devoted to results from dual junction (2J) cells.

BASIC CELL DESIGN AND I-V TESTING

$GaInP_2$/GaAs/Ge 3J epitaxial layers were grown at Spectrolab in a production MOVPE reactor incorporating high-efficiency cell structures suitable for the high current densities encountered at concentration under terrestrial conditions. The cells were fabricated using space solar cell device design modified for optimum performance under the AM1.5D terrestrial spectrum. The device cross section is shown in Figure 1, and has been extensively described elsewhere [3]. A major difference in these structures 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. The epitaxially grown layers were then processed with metal contacts and fabricated into concentrator cells by NREL for performance evaluation. Two types of devices each processed differently were fabricated at NREL.

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. Further, other wafers were processed into cells and tested at Spectrolab with an in-house HIPSS system. It should be pointed out that NREL has sent the record efficiency 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. All concentration levels were calculated by dividing the I_{sc} at concentration by the 1-sun I_{sc}. Also, measurements for performance evaluation under concentration are underway by Fraunhofer ISE.

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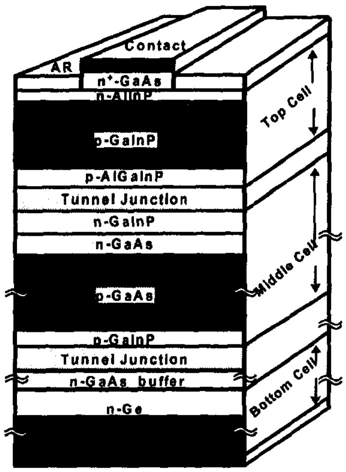


Figure 1:. Cross-section of triple-junction cell

TECHNICAL RESULTS AND DISCUSSION

Figures 2 through 5 are IV parameters based on Spectrolab- grown wafers that were processed into cells at NREL. Figure 2 shows a representative I-V curve for an early generation of small-area cells with the best cell yielding an efficiency of 32.3%. Figure 3 illustrates a family of curves of efficiency as a function of concentration. These curves were obtained from NREL with remarkably high values, and the concentration level was calculated by dividing the I_{SC} at concentration by the 1-sun I_{SC}. The efficiency reaches a maximum at 47 suns due to an unexpected "roll-off" in the open circuit voltage (V_{oc}) and then begins to decrease after 50 suns with an increase in intensity. This was somewhat surprising since V_{OC} normally increases linearly with the logarithm of short circuit current and concentration ratio. From several diagnostic experiments the roll-off was confirmed to be due to a less than ideal back contact that caused an opposing voltage to be generated at the illuminating intensities. Recently, other cells were processed and tested, and their device performance was higher than the performance of the earlier cells due to the elimination of this photovoltaic back contact [4].

Figures 4 and 5 show the V_{OC} and fill factor (FF) characteristics as a function of concentration ratios for the improved cells. The V_{OC} of the 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:

$$V_{oc3J} = V_{occ1} + V_{occ2} + V_{occ3} \approx \frac{kT}{q} \ln\left(\frac{J_{phc1} J_{phc2} J_{phc3}}{J_{oc1} J_{oc2} J_{oc3}}\right) \quad (1)$$

where J_{ph} and J_o are the photogenerated and the saturation current densities, respectively, for a given subcell, and c1, c2, and c3 designate subcells 1, 2, and 3 in the multijunction stack, and assuming that all subcells have the same diode ideality factor n. As the incident intensity increases by a factor of 10, the J_{ph} in each subcell increases by a factor of 10 and the change in V_{OC} for the 3J solar cell is $(nkT/q)\ln(10^3)$ = 196 mV/decade at 25°C for a diode-ideality factor of 1.1 for each subcell. For the best cell, the V_{OC} performs according to Eqn. (1) to concentration levels over 1000 suns, as shown in Figure 4. Figure 5 shows more detailed features of FF as a function of concentration for one of the best cells. A maximum occurs near 70 suns and then decreases steadily, but is still over 80% at 1000 suns. The drop in FF is due to the increased role of the series resistance at higher concentrations.

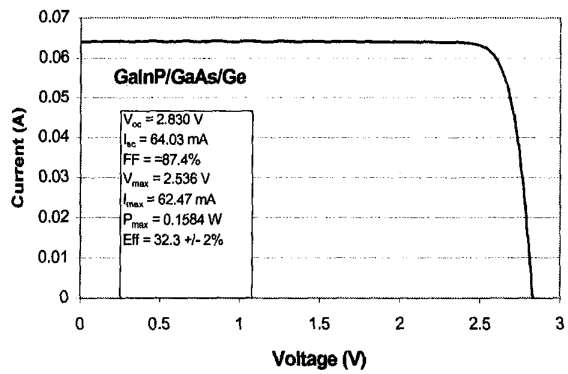


Figure 2: Light I-V characteristics of the best cell from the early generation of $GaInP_2$/GaAs/Ge 3J solar cells measured at AM1.5D and 47 suns by NREL.

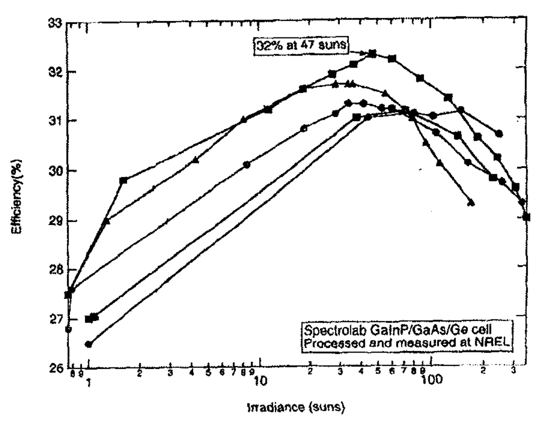


Figure 3: Spectrolab $GaInP_2$/GaAs/Ge 3J cell efficiencies versus concentration for 5 cells processed from the same wafer by NREL. These measurements are based on an early generation of cells.

Figure 6 shows the efficiency of the latest 3J cells with increasing concentration. The efficiency reaches a maximum of 32.4% near 372 suns and then decreases as the FF drops with rising concentration. Although these concentrator cells were designed primarily for 350 suns, they can be used for even higher concentration applications since the efficiency at 1000 suns, for

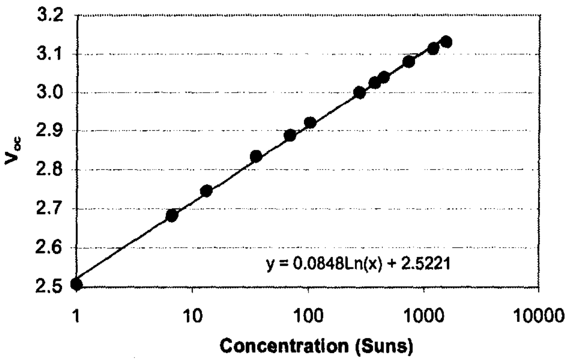


Figure 4: $GaInP_2/GaAs/Ge$ 3J cell open-circuit voltage versus concentration ratio.

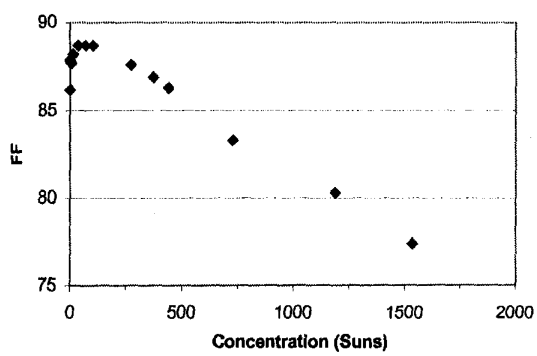


Figure 5: $GaInP_2/GaAs/Ge$ 3J FF dependence on the concentration ratio.

example applications since the efficiency at 1000 suns, for example, is near 31%, and is 29% at 1500 suns! Note that the peak efficiency occurs at higher concentrations compared to that in Figure 3 as a result of the device improvements.

I-V parameters were also obtained from in-house wafer processing of 3J and 2J cells, and both were tested at SPL as depicted in Figures 7-9. As with the NREL-processed wafers, the V_{oc} follows the logarithmic linear dependence on increasing concentration for both types of cells, as shown in Figure 7. The FF (Figure 8) also follows the same trend as that of NREL but the values from the SPL-processed wafers are somewhat lower throughout the concentration range studied for 2J cells. Factors to consider that could account for this difference are the use of substrates with different polarity types when building 3J cells as opposed to 2J cells, and the variation in processing techniques employed from each organization such as, metal deposition differences. Figure 9 shows that the efficiency for 3J cells reaches a maximum of 32.5% near 250 suns whereas that for 2J cells is at 29.6% near 160 suns.

A wide-bandgap tunnel junction was used in between the GaInP top cell and the GaAs middle cell, in order to

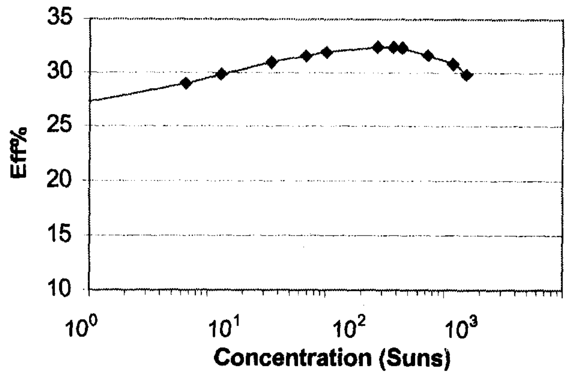


Figure 6: $GaInP_2/GaAs/Ge$ 3J cell efficiency dependence on the concentration ratio. The efficiency values are based on AM1.5G, 1000 W/m^2.

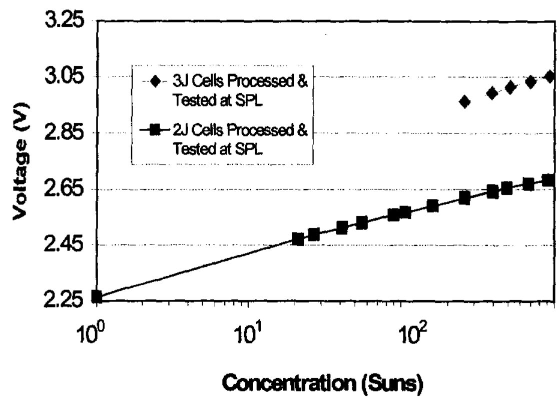


Figure 7: $GaInP_2/GaAs/Ge$ 3J cell V_{oc} dependence on the concentration ratio for Spectrolab-grown, processed and tested cells.

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.

As multijunction solar cells continue to make large strides in semiconductor device design for space applications, the terrestrial industry, in turn, will benefit tremendously from the substantial improvements in their performance. Cell efficiencies as high as those mentioned in this study convey a remarkable message: in their present state, 3J 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 at concentration levels higher than 500 suns, the efficiency is still over 30%, and, indicates that a concentrator system populated with such cells would yield a power output greater than twice the output of commercial Si cells with 15% efficiency at an equivalent concentration. Larger area 3J devices of 1 cm^2 designed at Spectrolab for operation above 300 suns, with no roll-off in V_{oc} have been developed as shown in Figures 7-9. While this will drive the cost per watt of the cells to even lower rates, the challenge will be to design cells where the external losses (i.e., losses that are outside the semiconductor layers of the device structure) are reduced to a minimum.

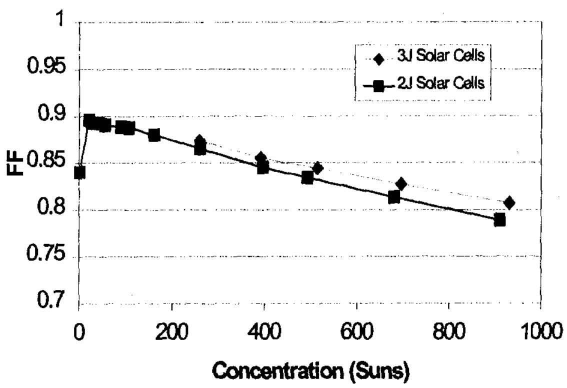


Figure 8: $GaInP_2$/GaAs/Ge 3J cell FF dependence on the concentration ratio for Spectrolab-grown, -processed and –tested cells.

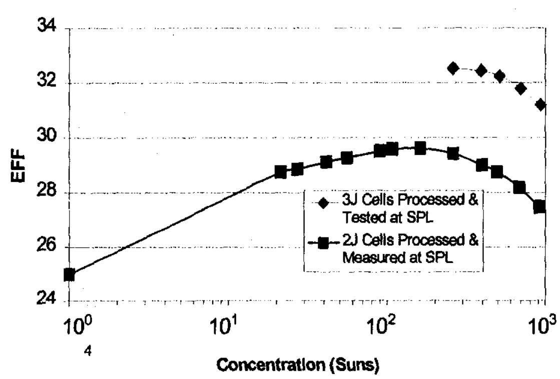


Figure 9: $GaInP_2$/GaAs/Ge 3J cell efficiency dependence on the concentration ratio for Spectrolab-grown, processed and tested cells.

TOTAL MANUFACTURING YIELD AND PERFORMANCE IMPROVEMENTS ROAD MAP FOR MULTIJUNCTION SOLAR CELLS

Considering that multijunction solar cells were suggested over two decades ago [5] to achieve very high-solar cell efficiencies, their implementation for space power systems has been relatively recent. Reasons for the lack of progress included both the unavailability of high-quality source materials to obtain semiconductor layers with long diffusion length, and to the absence of large MOVPE growth systems for cost-effective manufacturing of lattice-matched, solar cell materials. The driving need for large power systems in the 10kW range for direct broadcast satellites, and the future need for power systems approaching 25 kW, coupled with government needs for higher power systems sparked Spectrolab to re-think the use of resources to bring this technology to the marketplace. These constitute major R&D, manufacturing technology, and capital equipment investments made in the 1990s. Technical progress has been rapid and today, multijunction cells are the baseline technology for providing primary power for virtually all large space power systems.

Spectrolab, alone, has manufactured more than 460 kW of dual junction and over 30 kW of triple junction cells for space satellites. Over 85 kW of this product is now operating flawlessly in space. This is equivalent to about 175 MW of terrestrial solar cells at 500 suns concentration ratio! Global industry capacity for terrestrial multijunction cells almost certainly exceeds 500 MW per year (measured at these concentrations). Although only a portion could be allocated for terrestrial use, it is an important point to note that the equipment investments have already been made, and a portion of these assets are ready to be put to work for cost-effective terrestrial manufacturing.

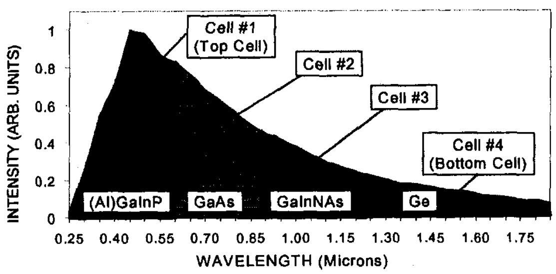
Significant leverage of space solar cell improvements on the performance of terrestrial solar cells is summarized in Figure 10. Differences in the illuminating spectrum together with the elimination of the requirement for radiation hardness, generally result in a higher conversion efficiency of a given cell product type under a concentrated AM1.5D spectrum than under the 1-sun AM0 spectrum. This is after the cell layers have been optimized for that particular spectrum.

In practicality, state-of-the-art, minimum average production efficiency for planar (1 sun) 3J space solar cells is approximately 26% (now available), and 30% for improved, state-of-the-art, 3J space cells at 1 sun AM0. The same products, once optimized for the terrestrial spectrum, can achieve minimal average production efficiencies over 29% and 30%, respectively, at 1 sun and AM1.5D. New 1-eV materials currently being developed for space will allow minimum average efficiencies of over 40% within the next few years (500 suns, AM1.5D). This prediction is based on relatively conservative modeling using realistic cell loss mechanisms, and production distributions that allow high manufacturing yields, and is also supported by the empirical data reported here. Indeed, Friedman *et al.* [6] and Kurtz *et al.* [7] have predicted idealized efficiencies for improved 3-junction and

4-junction cells utilizing new 1 eV materials, as high as 47% and 52%, respectively when illuminated under an AM1.5D terrestrial spectrum at 500 suns concentration. No other solar cell technology realistically offers the same opportunity to achieve such high conversion efficiency at relatively modest technical risk, and affordable cost.

KEY CHALLENGES FOR COST EFFECTIVENESS AND GROWTH OF MARKET SHARE

The key issues to be addressed before industry-wide acceptance of III-V concentrator systems are those of cost and reliability. Present industry perceptions are that multijunction solar cells are too costly for use in terrestrial systems and that the optics and trackers in which they operate are complex and unreliable.



	Minimum Average Production Efficiency Contribution (AM0, 28 C)			
	2J GaInP2/GaAs	3J GaInP2/GaAs/Ge	3J AlGaInP/GaAs/GaInAs	4J AlGaInP/GaAs/GaInAs/Ge
Cell 1	13.7%	13.7%	17.2%	17.2%
Cell 2	9.9%	9.9%	10.4%	10.4%
Cell 3		2.4%	6.1%	6.1%
Cell 4				1.6%
Min Av Production, 1 sun AM0	**22.0%**	**26.0%**	**30.0%**	**35.2%**
Idealized Efficiency (AM0)(1)	31.0%	35.0%	38.0%	41.0%
Min Av Production AM1.5D, 500 suns	**26.0%**	**30.0%**	**35.0%**	**40.0%**
Idealized Efficiency (500 suns, AM1.5D)(1)	36.0%	42.0%	47.0%	52.0%

[1] Friedman et al, 2 nd WCPEC, Vienna, 1998

Figure 10: Estimated minimum average production efficiencies by product type empirical data reported here.

Furthermore, there is a belief that their application is limited to all but the largest stand-alone utility systems, that are in themselves the most cost-competitive with existing energy sources. However, the widespread adoption of III-V solar cells for commercial and government space applications, as described earlier, has brought about large reductions in raw material costs, and increases in manufacturing yields. Given these cost reductions, and their proven reliability in space power systems, III-V solar cells used in medium to high concentration ratio systems may offer one of the best opportunities for energy generation cost reductions over the next few years, when compared to other PV technologies.

COST REDUCTION

Target system costs of $3/W [8] will require "bare cell" costs to be on the order of $0.5 to $1 per watt depending on the particular concentrator module and system design. These are very aggressive targets, but ones that can likely be achieved by systematically addressing major cost drivers such as the cost of raw materials (the Ge wafer presently comprises over one third of the overall cell price), direct labor, and performance improvements. Since the $/watt cost at the cell level reduces approximately linearly with concentration ratio, (because cell cost in $/cm2 is largely independent of concentration ratio), there are substantial advantages in operating cells at medium to high concentration ratios as shown in the cost projections of Figure 11. Several different cost vs. concentration ratio scenarios are included in this figure, namely:

1. 30% efficient 3J cells (these are considered to be immediately available in large quantities in year 2000)
2. 30% 3J cells manufactured using lower price wafers procured to a "terrestrial specification" (it is assumed that concentrator cells will be more forgiving of wafer specification compared to 1 sun space cells because of reduced influence of defects on performance at higher current densities)
3. 40% efficient, 4-junction cells that are assumed to be available within the next 2 to 3 years.

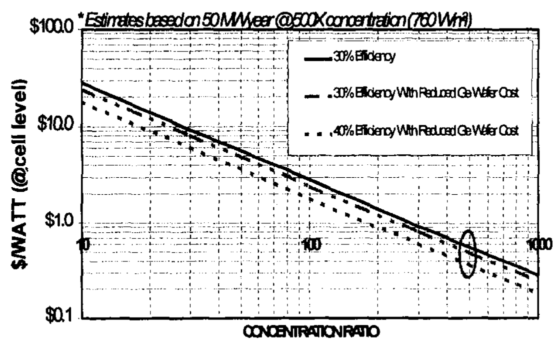


Figure 11: Estimated cell cost in $/W vs concentration ratio for different product types.

For each of the scenarios shown it was assumed that efficiency remained constant over a wide range of concentration ratios, and that 40% efficient 4-junction cells will ultimately cost no more than a 30% triple junction cell, when manufactured in high volume. These are reasonable first-order cost assumptions that have certainly been validated by a highly competitive space industry over the last several years. Furthermore, a manufacturing rate of about 50 MW/year was assumed corresponding to a throughput of about 150,000 wafers (of 100 mm diameter) per year. Under these assumptions, terrestrial concentrator cells can be cost effectively manufactured today, to provide the PV industry with cells in the range of $0.5/W to $0.6/W at 500 suns concentration, and about $0.5/W if a lower price Ge wafer is available to an acceptable specification. The development of solar cells of >40% efficiency will further reduce manufacturing costs to between $0.3/W and $0.4/W within the next few years, at relatively modest risk. These costs are highly attractive with respect to achieving the DOE cost goals, when put into the concentrator module manufacturer's cost models or linear, point-focus fresnel, and dish-based concentrator systems.

RELIABILITY

Both 2J and 3J solar cells have been extensively qualified for space application, and have undergone the rigors of long periods of illumination, temperature-humidity testing, deep thermal cycling, and shock and vibration testing without degradation. However terrestrial environments are extremely challenging, and the effects of long term exposure to concentrated sunlight (i.e. 500 suns or more), and the adequacy of existing cell packaging technology, are not well understood at this time, and should not be underestimated. Each of these issues must be proactively addressed through controlled laboratory and extensive field tests before multijunction cells can be widely implemented in terrestrial systems. This is an area where both government laboratories and industry must each play active roles.

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 47 suns and AM1.5D. The improved back contact of a more recent group of 3J cells showed the absence of the V_{oc} "roll-off" giving a slightly higher efficiency of 32.4% as measured by NREL. 3J and 2J cells built at Spectrolab showed the logarithmic-linear dependence of the V_{oc} on concentration, with maximum efficiencies of 32.5% and 29.6% at 250 and 160 suns, respectively. These numbers compare well with those measured by NREL.

Low-risk improvements will allow high-volume, industry-wide availability of cost-effective, 30% efficiency cells in the near term at a cost of between $0.5 to $0.6/W, at production volumes of about 50 MW/year. For the longer term, the opportunity exists for 500X concentrator cells costing <$0.4/W through the introduction of improved 4-junction solar cells based on new 1-eV materials, currently being developed for space solar cells.

A significant immediate challenge is to achieve market acceptance of this new technology. Once this is established, through laboratory-based reliability testing and multiple field demonstrations, demand for multijunction cells and concentrator systems could grow very rapidly due to the near-term cost reductions afforded by this new technology.

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