PROGRESS IN HIGH-EFFICIENCY TERRESTRIAL CONCENTRATOR SOLAR CELLS[1]

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Abstract. Multijunction solar cells based on III-V semiconductors are the most efficient solar cells in the world, with record efficiencies of over 40%. These devices offer the promise of very competitive solar power systems exploiting the high efficiency devices under high optical concentration. To make this promise a reality, Spectrolab is conducting a multi-year program to develop solar cells with still higher efficiency and substantial cost reductions and to fully characterize and qualify them for reliable performance in the field. Qualification of a second generation cell technology has recently been completed. Cell performance, qualification, and field test data will be presented; progress on performance improvements, cost reductions, and manufacturing capacity plans will be discussed. Development of these high-performance multijunction CPV cells promises to break the bottleneck currently limiting growth in photovoltaic power generation.

Introduction. Multi-junction solar cells have emerged from a long history of development [1-6] focused initially on space applications. The emergence of high quality triple-junction cells with substantially higher efficiency than crystalline silicon spurred interest for terrestrial application exploiting these cells in high optical concentration systems [see, for example, ref 7]. Realization of cells with efficiency exceeding 40% in the laboratory [8-10] has led many observers to expect that concentrating photovoltaic (CPV) systems will be able to deliver solar power at the lowest cost among competing technologies, at least in areas with high direct normal insolation [11].

Since introducing triple-junction cells to the CPV market in 2004, Spectrolab has adopted an aggressive but achievable roadmap for both cost reduction and efficiency improvement, funded by internal R&D and capital investments as well as support from the US Department of Energy's Solar America Initiative. In order to address the market need for rapid improvement in cell efficiency, we defined a planned series of improved cell product design generations to be implemented in parallel with numerous product cost reduction initiatives. The technology designation, target efficiency, and production dates for the product generations developed or planned through 2010 are as follows:

Technology	Initial Production	Average Efficiency*
C1MJ	2004	37.0%
C2MJ	June 2008	37.5%
C3MJ	Sept 2009	38.5%
C4MJ	Mid-2010	40%

* 25°C, ASTM 173G at 50 W/cm^2

Figure 1 summarizes the planned improvements in the economics of Spectrolab multi-junction cells, reflecting both efficiency improvements, which leverage the cost of the entire system by increasing the power output of the system in proportion to efficiency, and cost improvements, which are themselves also leveraged by efficiency improvements. This paper provides an overview of the work ongoing at Spectrolab in the areas of cell efficiency, factory cost reduction, and qualification for long-term reliability.

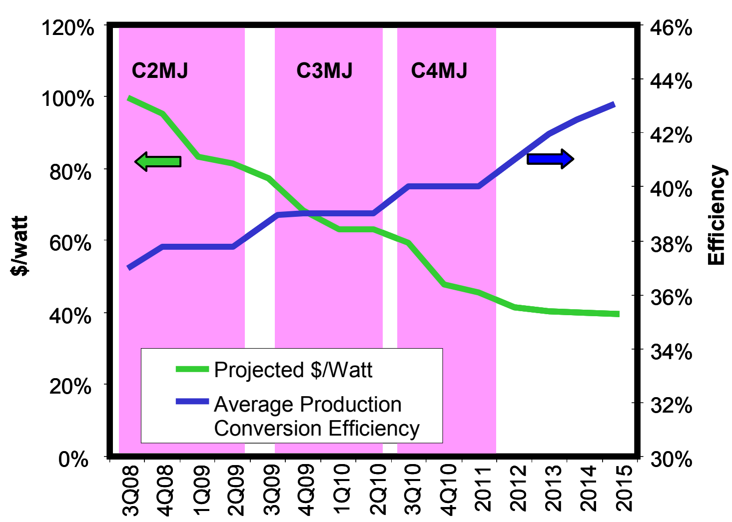

Figure 1. CDO-100-IC Cell Cost and Efficiency Roadmap

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Efficiency Improvement. The efficiency improvements on the roadmap shown in Figure 1 will be achieved through fundamental improvements in the epitaxial device structure and through various improvements in processing at the wafer level.

The design improvements implemented for the C2MJ process consisted of improvements in front metal patterning. It is well-known that shadowing of the semiconductor surface by the metal fingers that collect and conduct the photocurrent to the external circuit is an important loss mechanism [12]. This is particularly true for cells designed for high concentration, since the current and hence metal density are correspondingly higher [13]. Photoresist and metal deposition processes were modified to increase gridline aspect ratio (height / width). This allows grids to conduct equivalent or higher current while also admitting more light to the active layers. C2MJ uses the same epitaxial wafer as C1MJ, but generates extra current as a result of the reduced gridline shadowing. The modeled and measured result was an average of 0.5% absolute efficiency improvement over C1MJ. Spectrolab began high volume production of C2MJ in May 2009.

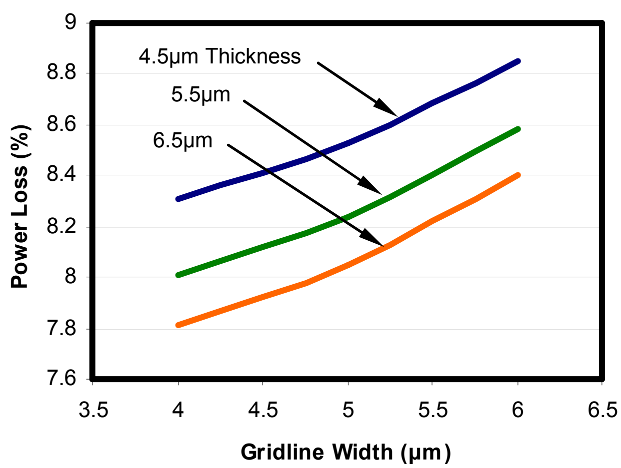
Further changes in gridline metallization are planned for the next cell generation. These include optimization of the gridline spacing based on actual metallization geometry, and further increasing the aspect ratio of gridlines compared to the C2MJ and C3MJ design. Figure 2 illustrates the effects of gridline dimensions (width, height, sidewall angle etc.) on optimum pitch and on resistive loss.

The C3MJ design retains the same wafer metallization processes that were qualified in the C2MJ process, but also incorporates an improved epitaxial design. The epitaxial process for C1MJ and C2MJ cells is common to both. The C3MJ top cell band gap is higher than that of the C1MJ/C2MJ process but the top cell is thicker, resulting in a more sharply defined absorption edge as shown in the spectral response comparison in Figure 3.

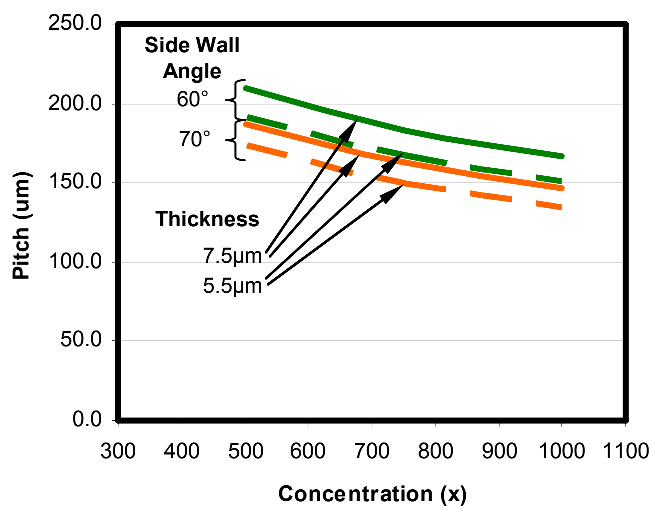
Figure 4 shows the resulting progression in production efficiency distribution for each of the three product generations. Cells were tested using the Spectrolab standard production test high concentration pulsed solar simulators. The simulators are set up using isotype component cells with calibration traceable to JPL balloon flight cells. Spectral mismatch calculations were used to generate ASTM173G calibration values for the balloon traceable standards. Several sets of CPV calibration standards were generated, with one set of standards each being calibrated by Fraunhofer, NREL and AIST. All measurements were done blind.

Over the medium to long term, we expect to introduce improvements to the fundamental epitaxial structures used in multi-junction devices, as illustrated in the device structure roadmap of Figure 5. All of our production cells to date have been lattice-matched, with the indium content in the middle cell selected to match the lattice constant of the germanium substrate, and the compositional balance of the GaInP top cell similarly constrained. This still affords engineering of the top cell bandgap by means of controlled disordering of the (In,Ga) sublattice [14]. Lattice-matched cells have the obvious advantage of being a proven technology, and the ability to grow structures of very high crystal quality has been demonstrated. Further evolution of the lattice-matched approach is certainly possible, with promising candidate device architectures in 4, 5, and 6-junction configurations.

All of the production devices produced thus far



(a) Power loss due to grid fingers of varying thickness and width



(b) Optimum grid pitch as a function of grid finger geometry

Figure 2. Front Metal Optimization Trades.

have been lattice-matched cells, but to reach the 40% production efficiency goal for 2010, we have selected the metamorphic technology as the baseline approach. The metamorphic cell has a step-graded buffer layer between the bottom germanium cell and the middle cell to transition to a slightly larger lattice constant Ga(In)As middle cell, upon which is grown a lattice matched GaInP top cell; the middle and top cells more closely match the optimum bandgap combination for the solar spectrum, and higher efficiency cells in this configuration have been demonstrated [15, 16]. In the longer term, several promising research vectors exist for higher efficiency cells. These include inverted metamorphic technology [17], as well as upright metamorphic and lattice matched approaches.

Production Automation and Cost Reduction. The technology for multijunction devices has evolved from the space power industry, which has much lower volume than is expected for terrestrial CPV systems, and therefore had little need for the types of automation used in the broader semiconductor industry. Spectrolab is undertaking a major capital improvement program to address the needs for higher throughput and lower cost of terrestrial solar cells. As illustrated in Figure 6, this factory improvement includes upgrade of our epitaxial growth capabilities with new MOCVD reactors offering larger capacity per run, more automated operation, and much finer control of process variables for reduced performance variability; and automation of welding and testing processes to reduce touch labor during the cell assembly process.

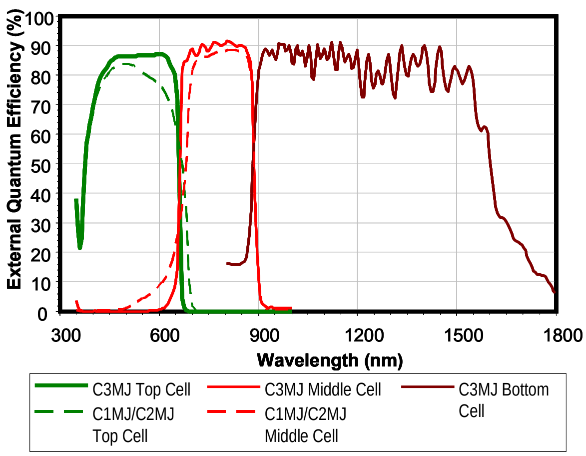


Figure 3. C1MJ/C2MJ versus C3MJ Spectral Response

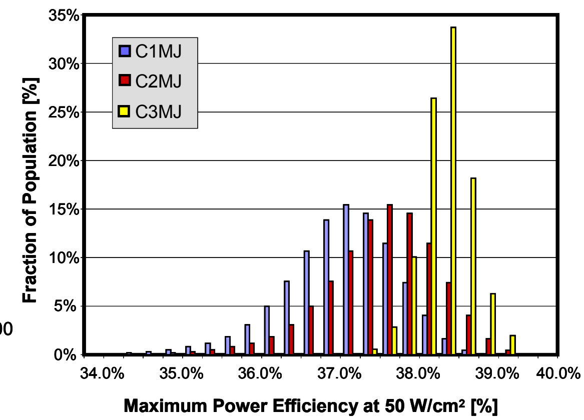


Figure 4. Production Efficiency Histograms for C1MJ, C2MJ and C3MJ Cells (at 50 W/cm² illumination)

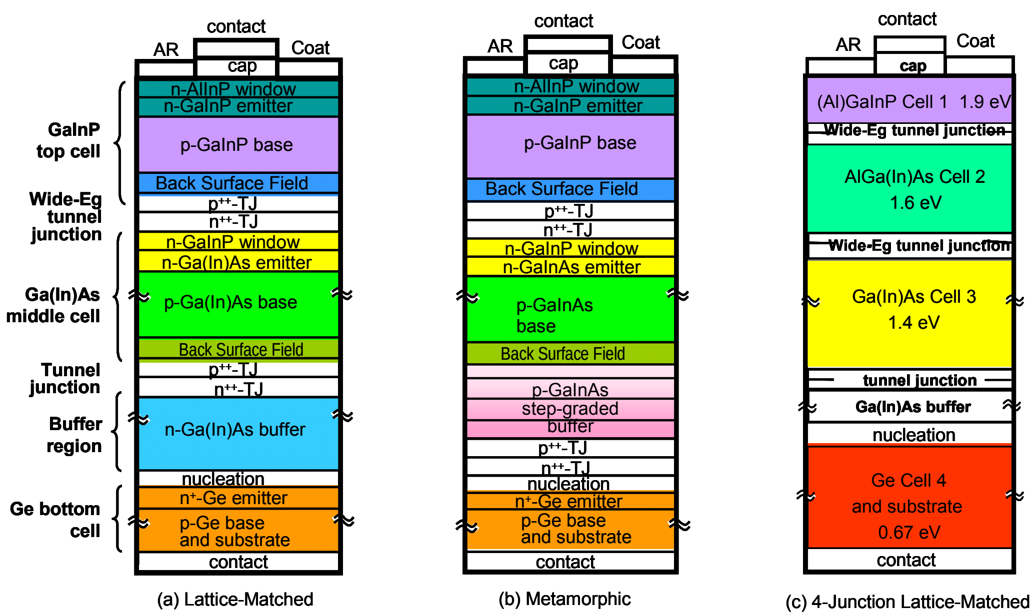


Figure 5. Cell epitaxial structure development roadmap

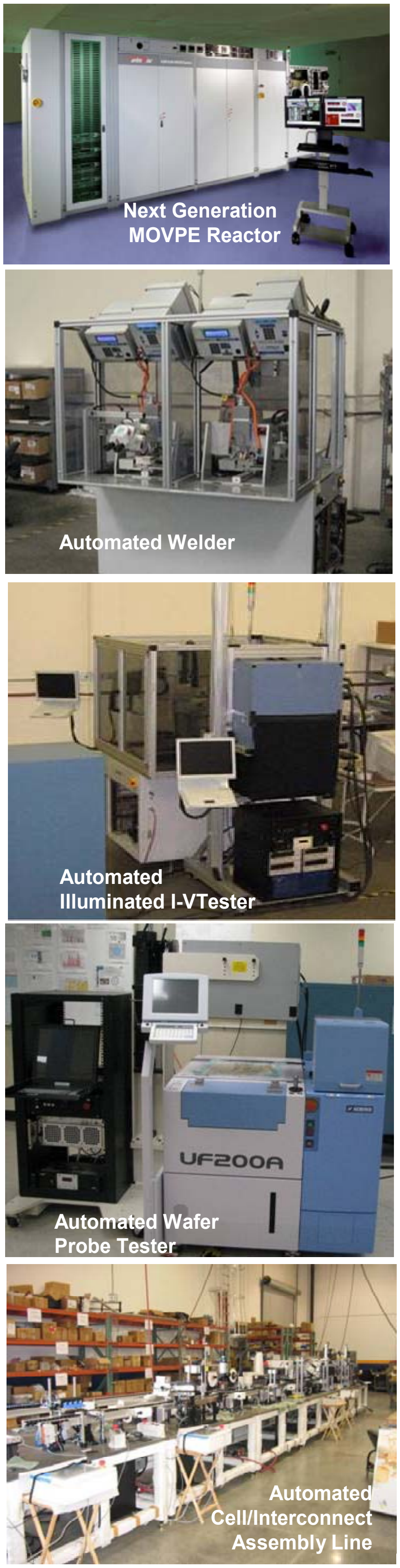


Figure 6. New Factory Automation Equipment at Spectrolab.

A key component in Spectrolab's efforts to improve efficiency and reduce cell cost is the adoption of a next generation MOVPE reactor platform. Spectrolab is currently operating 3 of the new reactors with plans to transition all epitaxial operations to this platform in the next couple of years. Next generation MOVPE tools are optimized for a 150mm (6 inches) wafer size, but already offer a higher capacity, shorter cycle time, and reduced material costs on our current 100mm (4 inches) germanium substrates.

Next generation tools include a series of advanced in-situ process diagnostics including real-time emissivity-corrected pyrometers, a deflectometer for measuring wafer bow in real-time, and binary gas concentration monitors. Together, these diagnostic instruments provide improved process visibility and control for reduced performance variability.

Epitaxial wafer growth recipes supporting C1MJ, C2MJ, and C3MJ CPV product generations were rapidly adapted to the new tool platform and all have successfully completed a series of delta qualification tests. The next generation tool has also been the main platform for process development for the 40% C4MJ, to take full advantage of all the tool capabilities.

Automation of two key manual labor steps, interconnect welding and illuminated I-V performance testing, was successfully completed in 2007 through mid-2008. The automatic tester also automatically sorts cells into closely matched performance bins so that customers can use matched cells to minimize performance losses in series strings. The next iteration in automation of those steps is to integrate both welding and illuminated testing in an automated assembly line (AAL) (last photo of Figure 6). We are beginning initial production with the integrated AAL now; it is expected to be able to produce 70 MW per annum from a single line (assuming 500 suns concentration). The result thus far of implementing just the welding and test automation has been an 82% reduction in cell assembly touch labor.

In the latter half of 2008 and early 2009 we successfully implemented fully automated testing at the wafer level (4^{th} photo). This provides a flexible test capability for cells of any size, again with cells sorted into matched performance bins, via an electronic map delivered with the wafer.

Figure 7 illustrates the cost reductions expected through these and other automation improvements. Major automation steps for the coming year include automated production of punched interconnects and pick and place automation of cells in the saw dicing process.

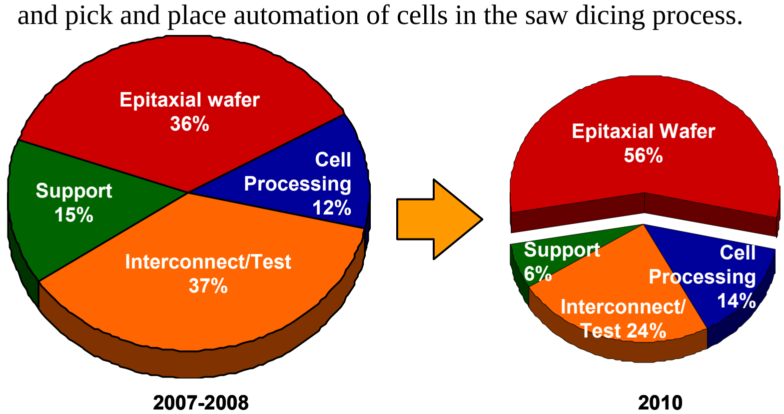


Figure 7. Reallocation and rescaling of costs as a result of factory automation cost reductions.

Qualification and Field Testing. The space heritage of this technology has mitigated many reliability risks for CPV customers due to the extensive qualification testing, flight performance history, and generally strong emphasis on reliability for Spectrolab PV products. However, there are significant differences between space and terrestrial environments, as summarized in Figure 8 [18]. Accordingly, Spectrolab has defined a qualification program addressing these environments and the IEC-62108 standard and subjected our concentrator cells to those tests. Qualification of both C1MJ and C2MJ has been completed and it is expected that C3MJ qualification will be completed by September 2009.

C1MJ, C2MJ, and C3MJ qualification parts have been grown on the new K series MOVPE reactors. The new reactors require some operating, growth and control changes. As familiarity with the reactor increases, Spectrolab expects tighter, more consistent distributions and improved performance from better crystal quality. Slight adjustments to growth conditions have already improved voltage by 30 mV over the initial results. Parts are now being built to demonstrate the improved voltage. These steps are part of the process to qualify the new reactors for production, which has now been completed.

The purpose of qualification testing is to exercise the cells for known failure and degradation mechanisms so that users can have confidence in the long-term reliability of the cells. Since use of the cells in terrestrial applications is relatively recent (triple-junction cells have been in use in space since 2003, and earlier dual-junction cells for about a decade), ongoing field trials are important to establish the long-term reliability. One of the best such trials is being undertaken by Solar Systems in Hermannsburg, Australia, where the first multi-junction receiver was placed in service in March of 2006 (Figure 9). The field was subsequently upgraded to include four dishes with multi-junction receivers, and the data in Figure 9 are from all four systems. The quantity plotted is the energy production rate (EPR), which is defined as

$$EPR = \frac{\text{Energy generated by dish system per day}}{\text{Solar energy incident on one } m^2 \text{ of collector per day}}$$

Environment	Unit	Space[1]	Terrestrial	
Mission duration	yr	15	25	
Sun hrs per year	hr	8,760	2,700 to 3,400	
Operating Temp	°C	-180 to 70	-20 to 100	
Equivalent life @ 70°C	yr	15	2 to 36[2]	
Thermal cycle				
# of cycles		20,000--80,000	60,000	
Avg Temp Range	°C	-100°C to + 100	0--70	
Substrate CTE	ppm	-2 to 6	5 to 8	
UV radiation	W/m^2		Primary	Cell[3]
UVA	W/m^2	85	22	21790
UVB	W/m^2	17.4	0.21	210
UVC	W/m^2	6.9	0	0
Ambient		Indoor air – 5 yr Vacuum - 15 yr	Outdoor air	
Moisture		indoor, controlled	outdoor, uncontrolled	
Current Density	A/cm^2	0.017	6 to 14	

1. GEO mission used for duration & operating temp. LEO orbit used for thermal cycling
2. Calculated from TMY2 data for Phoenix, AZ, Dagget, CA and Pueblo, CO. Assumes cell temp = T_a+50°C & cell E_a = 0.8 to 1.2
3. 1,000 sun concentration

Figure 8. Space and terrestrial environments drive qualification requirements.

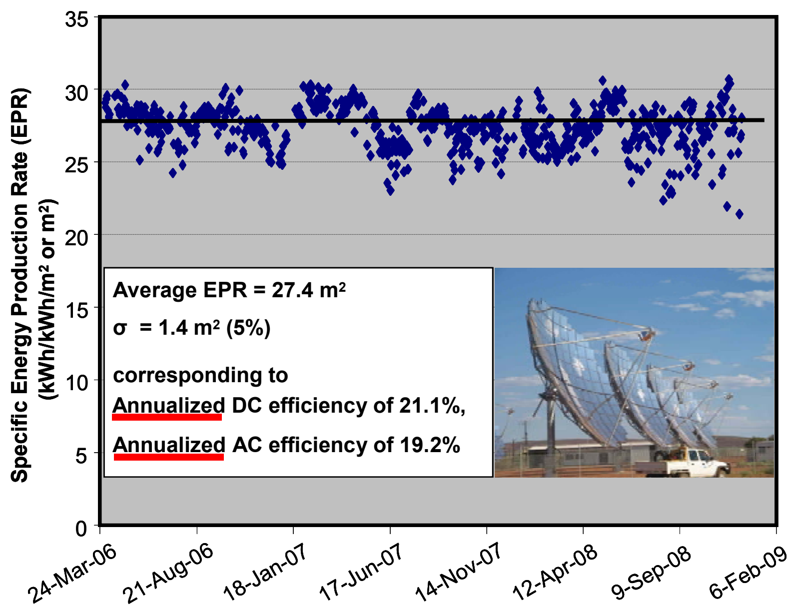


Figure 9. Field tests by Solar Systems Pty, Ltd in Hermannsburg, Australia

This calculation is useful since to first order one expects this quantity to be constant; in reality it varies slightly due to factors such as spectral content changes throughout the day. The data reflect little or no degradation over the test interval (i.e., any degradation is within the error bounds of the measurements).

Conclusions. Multi-junction cells have the potential to enable CPV systems delivering the lowest cost solar power in high insolation regions. Spectrolab is making investments in efficiency improvement, factory automation, and qualification test to rapidly improve the cost effectiveness of this technology.

References:

[1] Kamath et al, "Large-Area High-Efficiency (AIGa)As-GaAs Solar Cells," *IEEE Trans. Electron Devices*, Vol. ED-24, No. 4, p. 473, April 1977

[2] Virshup et al, "23.9% Monolithic Multijunction Solar Cell," *IEEE Photovoltaic Specialist Conference*, p. 441, 1988.

[3] Iles et al, "High-Efficiency (> 20% AMO) GaAs Solar Cells - Grown on Inactive-Ge Substrates," *IEEE Electron Device Letters*, Vol. 11, NO. 4, p. 140, April 1990

[4] Harris et al, "Development Of Stacked Multiple Bandgap Solar Cells," 1979 International Electron Devices Meeting, Volume 25, p. 694, 1979.

[5] J.M.Olson, S.R.Kurtz, and A.E. Kibbler, "A 21.8% GaInP2/GaAs Tandem Solar Cell," *IEEE Photovoltaic Specialist Conference*, p. 777, 1988.

[6] Tobin et al, "High Efficiency GaAs/Ge Monolithic Tandem Solar Cells," *IEEE Photovoltaic Specialist Conference*, p. 405, 1988.

[7] Verlinden et al, "Performance And Reliability Of Multijunction III-V Modules For Concentrator Dish And Central Receiver Applications," *4th World Conference on Photovoltaic Energy Conversion (WCPEC-4)*, Hawaii, May 2006.

[8] King et al, "Metamorphic Concentrator Solar Cells with Over 40% Conversion Efficiency," *4th International Conference on Solar Concentrators (ICSC-4)*, El Escorial, Spain, March 2007.

[9] NREL 40.8% IMM

[10] http://www.fraunhofer.org/News/ISE_PI_e_World%20Recod.pdf

[11] King et al., "Bandgap Engineering in High-Efficiency Multijunction Concentrator Cells," *3rd International Conference on Solar Concentrators (ICSC-3)*, Scottsdale, AZ, May 2005.

[12] Green, *Solar Cells: Operating Principles, Technology, and System Applications*, Prentice-Hall, 1982.

[13] King et al, "Advances in High Efficiency III-V Multijunction Solar Cells," *Advances in OptoElectronics*, 2007.

[14] King et al, *Advances in OptoElectronics*, 2007.

[15] Ibid.

[16] http://www.fraunhofer.org/News/ISE_PI_e_World%20Recod.pdf

[17] R. King et al., "New Horizons In III-V Multijunction Terrestrial Concentrator Cell Research," *Proceedings of the 21st European Photovoltaic Solar Energy Conference, Dresden, Germany*, September 2006.

[18] Hebert, "Qualification and Reliability of High efficiency Multijunction Concentrator Solar Cells for Terrestrial Applications," SPIE International Symposium on Solar Energy + Applications, August 2008.

[19] P.J. Verlinden and J.B. Lasich, *International Conference sor Solar Concentrators 5 (ICSC-5)*, Palm Desert, California, November, 2008.