STATUS OF 40% PRODUCTION EFFICIENCY CONCENTRATOR CELLS AT SPECTROLAB[i]

R.K. Jones, P.Hebert, P.Pien, R.R. King, D. Bhusari, R. Brandt, O.Al Taher, C.Fetzer, J.Ermer, A. Boca, D. Larrabee, X.Q. Liu, and N. Karam
All authors: Spectrolab, Inc., a wholly-owned subsidiary of the Boeing Company, Sylmar, California

ABSTRACT

Multijunction solar cells based on III-V semiconductors are the most efficient solar cells in the world, and of the established photovoltaic technologies, have the greatest potential for future growth in efficiency. Champion cells with efficiency greater than 40% have been demonstrated by several groups since 2006, and in that same period, the efficiency of cells in mass production has also increased steadily. These devices offer the promise of very competitive solar power systems exploiting the high efficiency under high optical concentration. To this end, 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. Development of the fourth production generation with 40% average production efficiency is nearing completion. Cell design and performance will be presented, with a summary of qualification and field test status. Progress in ongoing efforts to automate cell production for cost reduction and increased manufacturing capacity will be discussed. Development of these high-performance multijunction CPV cells is key to the emergence of CPV technology as the lowest cost solar power solution in high DNI areas.

INTRODUCTION

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 investments as well as support from the US Department of Energy's Solar Energy Technologies Program. 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 2011 are as shown in Table 1.

Table 1. Cell Technology Generations

Technology	Initial Production	Average Efficiency*
C1MJ	2004	37.0%
C2MJ	June 2008	37.5%
C3MJ	August 2009	38.5%
C4MJ	1^{st} Q-2010	40%

* 25^{o}C, ASTM 173G at 50 W/cm^2

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].

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 [8]. This is particularly true for cells designed for high concentration, since the current and hence metal density are correspondingly higher [9]. 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 used the same epitaxial wafer as C1MJ, but generated 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. The C3MJ design retained the same wafer metallization processes that were qualified in the C2MJ process, but also incorporates an improved epitaxial design. Volume production of C3MJ cells began in September 2009. Figure 1 shows efficiency distributions from the three generations of Spectrolab production cells based on large production samples (over 100,000 cells in each case). 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.

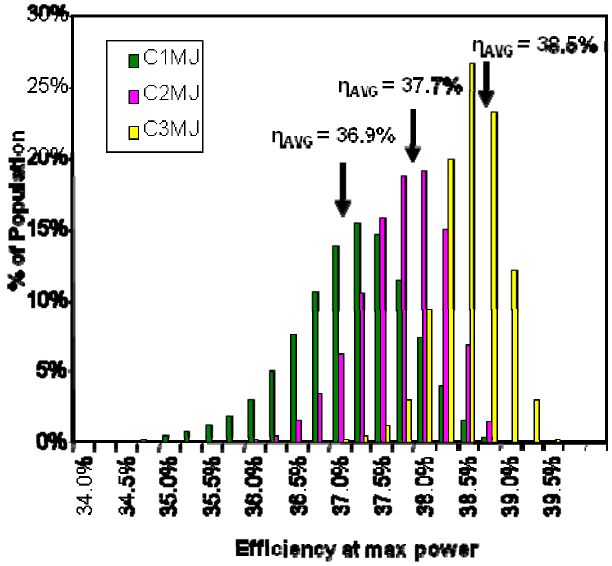


Figure 1. Evolution of production multi-junction cell technology through prior three generations.

The C4MJ cell is to be the first production metamorphic triple junction cell available. Figure 2 illustrates, by comparison, a typical epitaxial structure for lattice-matched and metamorphic devices. In a metamorphic device, the lattice spacing is transitioned from that of the growth substrate by means of a series of step-graded buffer layers that contain the dislocations within electrically inactive layers without degrading device performance. This paper describes current status of development of the C4MJ production metamorphic cell at Spectrolab, in

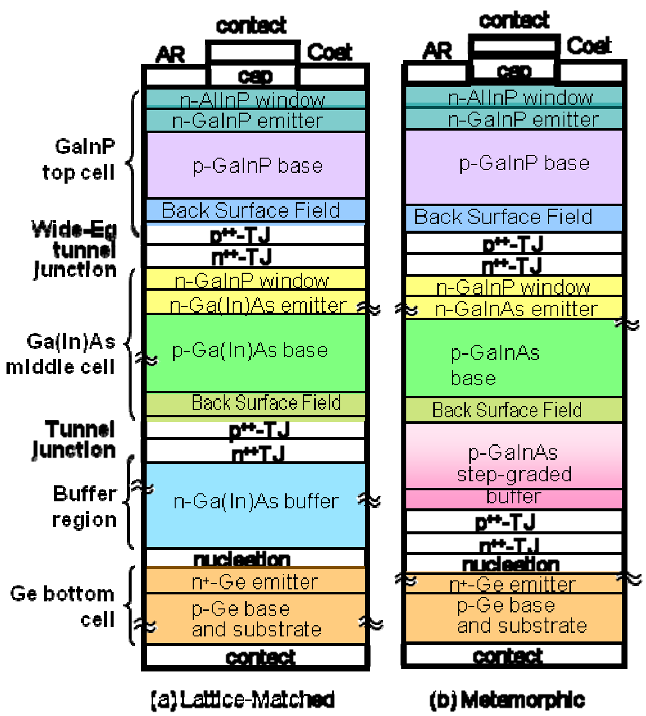


Figure 2. Lattice matched and metamorphic epitaxial structure.

context with the prior state of the art and expected future design directions.

RECORD EFFICIENCY METAMORPHIC CELLS

Realization of cells with efficiency exceeding 40% in the laboratory 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 [10]. Although the current record efficiency is held by a lattice-matched device [11], Spectrolab produced the first cells exceeding 40% efficiency, reporting both lattice-matched and metamorphic devices exceeding that threshold in December 2006 [12, 13]. Significantly, both lattice-matched and metamorphic performance records were achieved simultaneously, but the metamorphic device demonstrated higher efficiency than the lattice-matched approach for the first time, exceeding the best lattice-matched devices produced contemporaneously in the same lab by 0.6% absolute. A further record metamorphic cell was announced by Fraunhofer in January 2009 [14] with efficiency of 41.1%.

Figure 3 plots iso-efficiency contours for three-junction terrestrial solar cells at 240 suns concentration, as a function of the top and middle subcell band gaps. These are ideal efficiencies, calculated based on the fundamental mechanism of radiative recombination, the AM1.5D terrestrial solar spectrum, and the I-V characteristics of each subcell [15]. Band gap combinations of GaInAs and GaInP at the same lattice constant are also plotted, for GaInP with a disordered group-III sublattice (high Eg1) and for ordered GaInP (low Eg1). The various recent record efficiency lattice-matched and metamorphic three-junction cells cited above are plotted along with the design of the Spectrolab production C4MJ cell, showing the advantage of the metamorphic cell design in practice now, as well as in theory. Decreasing the band gap of the top two subcells, e.g., by raising the indium content, brings the

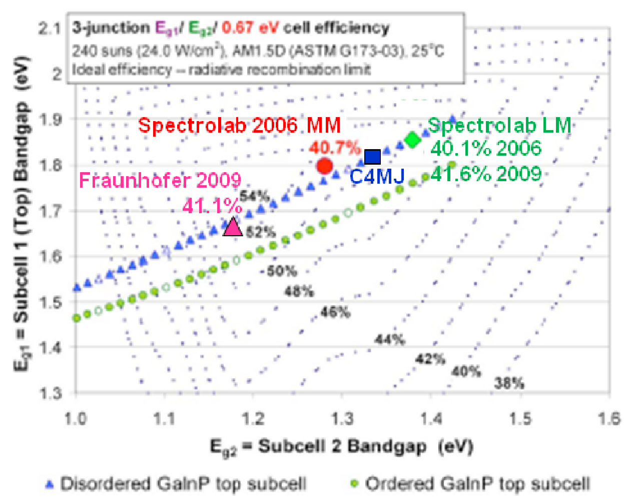


Figure 3. Metamorphic cell designs and radiative recombination efficiency limits.

three-junction cell design closer to the peak efficiency. The Fraunhofer cell demonstrated the largest mismatch of lattice constants from the growth substrate. The Spectrolab record metamorphic cell (as well as the C4MJ cell) use less lattice constant shift, but all designs take advantage of the wider top cell bandgap available through disordering of the top subcell.

C4MJ DEVICE DESIGN

All of the production devices produced thus far have been lattice-matched cells, but to reach the 40% production efficiency goal for C4MJ, we have selected the metamorphic technology as the design approach. The C4MJ is an n-on-p triple junction device structure which comprises a GaInP top cell and a GaInAs middle cell, both grown on an active germanium substrate. As such, it represents both an evolutionary step from its C1MJ, C2MJ, and C3MJ predecessors as well as the first introduction of metamorphic top and middle cells in a high-volume production design. Unlike previous record metamorphic device designs, with lattice-mismatch values of up to 1.2%, the C4MJ design employs a smaller mismatch value of just 0.35% to provide better overlap with the terrestrial spectrum, as well as a thinner buffer layer and reduced production run-time and cost. As in the case of more aggressive metamorphic device designs, the lattice-mismatched middle and top cells of the C4MJ are grown on top of a step-graded buffer which is fully relaxed and confines misfit dislocations that would otherwise degrade performance if propagated into active layers of the device structure.

Figure 4 provides a comparison between typical spectral response curves of new C4MJ device and previous generation cell designs. 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 4. Incorporation of approximately 5% Indium in the C4MJ GaInAs middle cell results a band-gap of about 1.34 eV. Matched to the middle cell is a disordered GaInP top cell with a band-gap of about 1.82 eV. With these adjustments to band gaps, the C4MJ experiences a gain in current approaching 10% while the accompanying loss in voltage is less than half that amount. Figure 5 shows the I-V curve for a typical 1 cm^2 C4MJ cell at 50 W/cm^2 irradiance. When combined with other improvements in cell design and fabrication, the relative net gain in performance is between 4% and 6% compared to the C3MJ cell, resulting in a C4MJ technology with a nominal device performance greater than 40%.

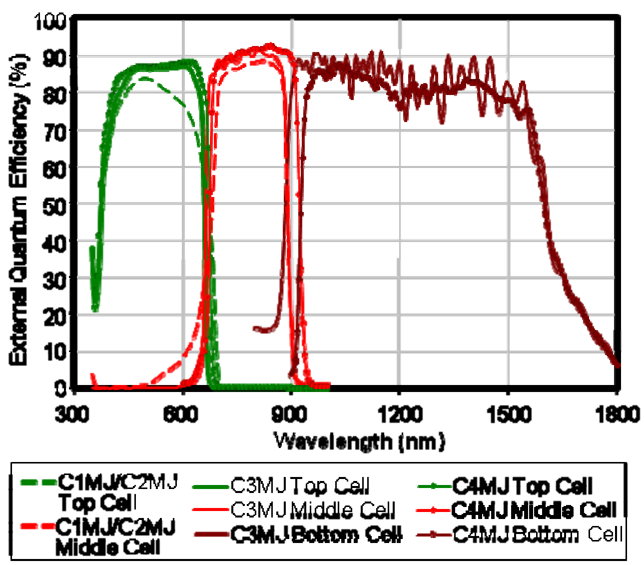


Figure 4. Comparison of measured typical spectral response of the C4MJ metamorphic cell with prior production device designs.

STATUS OF TESTING AND DEVELOPMENT

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 factory improvement program to address the needs for higher throughput and lower cost of CPV solar cells [16]. As illustrated in Figure 6, this factory improvement includes upgrade of our epitaxial growth capabilities with new MOCVD reactors, automated saw dicing, automated pick and place equipment for handling individual cells after saw dice, automated testing of both wafers and bare cells, and automated interconnect welding.

A key component in Spectrolab's efforts to improve efficiency and reduce cell cost is the adoption of a next generation MOVPE reactor platform. Next generation

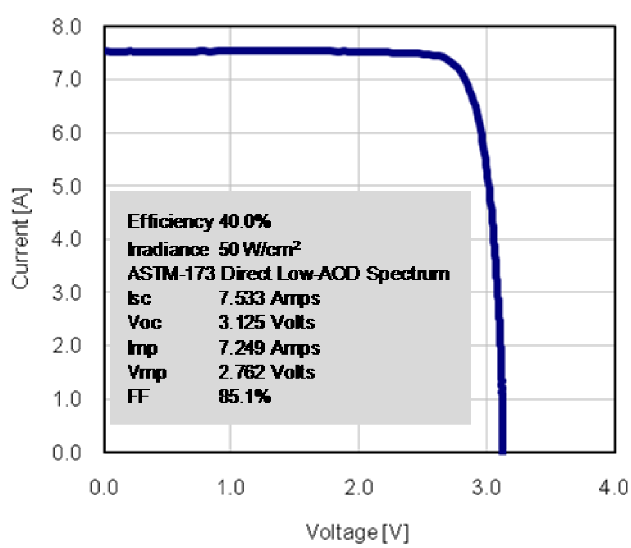


Figure 5. I-V Characteristics for a "typical" C4MJ cell.

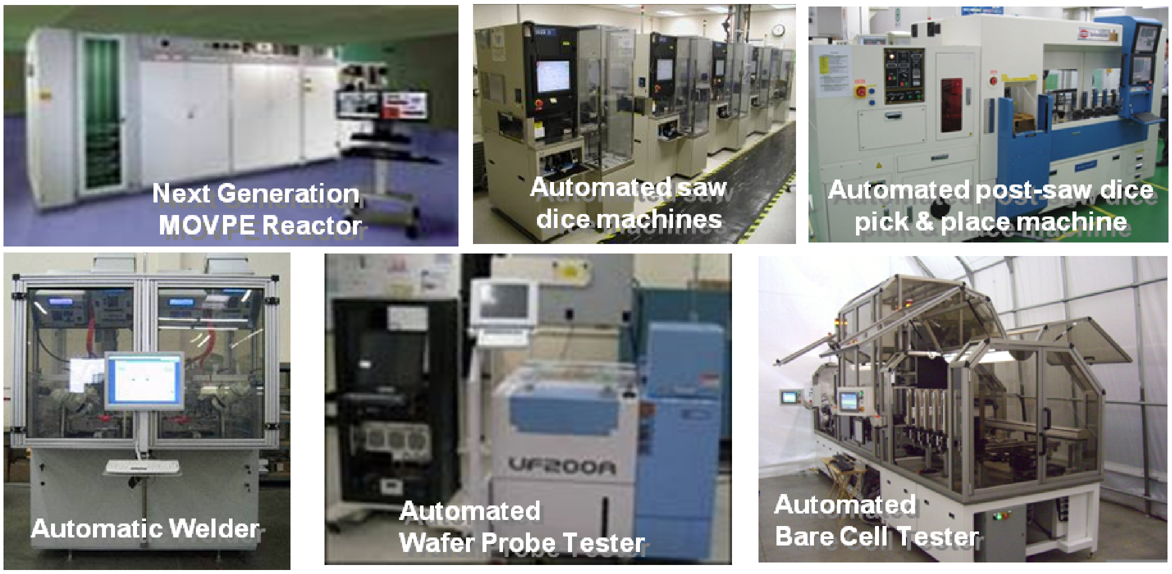


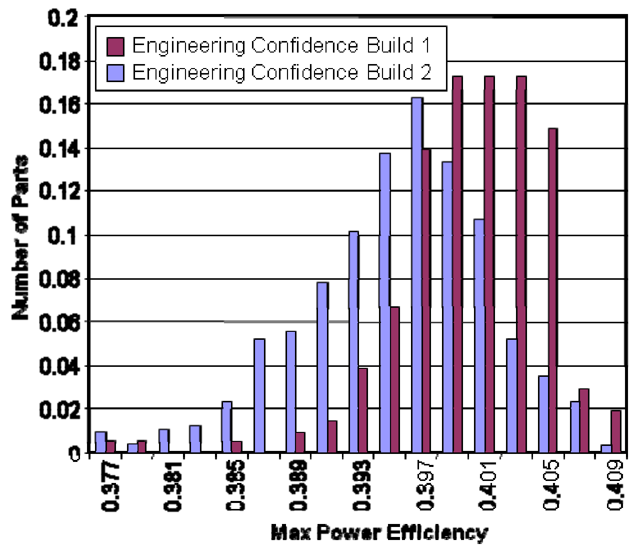
Figure 6. Upgraded factory production and test equipment for CPV products.

MOVPE tools are optimized for a 150mm (6 inches) wafer size, but also offer a higher capacity, shorter cycle time, and reduced material costs on our current 100mm (4 inches) germanium substrates. These 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. Prototype 40% cells for C4MJ take advantage of the in-situ wafer curvature capability of the K475 reactor to repeatedly produce upright metamorphic GaInP/5%-InGaAs/Ge cells with 100% crystal lattice relaxation, validated by 5-point maps of high resolution X-ray diffraction in run-to-run stability 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 [17]. However, there are differences between space and terrestrial environments, and accordingly, Spectrolab has defined a qualification program addressing these environments and the IEC-62108 standard and subjected our concentrator cells to those tests. C1MJ, C2MJ, and C3MJ cells have been subjected to our internal qualification process prior to offering them to customers in volume production.

Spectrolab's qualification program incorporates three gated reviews (Proof of concept, Internal Design Review and Qualification) to ensure a complete characterization of risk prior to production start. Proof of concept testing looks at basic device stability and performance. Internal design testing intentionally varies process parameters to determine specifications and ensure robust performance across the whole allowed range of variation. Qualification testing is primarily aimed at providing performance and reliability information to the market. All three phases of product introduction include testing parts from multiple reactors and multiple process lots as well as test and measurement controls. All efforts are made to include all sources of variation.

The C4MJ technology has completed proof of concept testing, has started internal design testing and is on track to begin production in January 2011. Figure 7 shows test results from early engineering confidence production batches. LIV performance was measured using isotype set up standards calibrated by NREL. A second set of



	Voc [V]	Isc [A]	Vmp [V]	Imp [A]	Pmp [W]	FF	Eff [%]	Count
Eng.Conf. Build 1	3.146	7.440	2.779	7.198	20.004	0.855	40.0%	208
Eng.Conf. Build 2	3.135	7.502	2.731	7.243	19.78	0.841	39.6%	1574

Figure 7. Results from Pre-Qualification engineering confidence builds of C4MJ cells.

Test	Conditions	Requirement	Results
Performance	50 W/cm²	η_{avg} > 37.6% target η_{avg} = 40.0%	η_{avg} = 39.7%
Thermal cycle	1000 cycles, –40°C to +110°C	unprotected cell <2% degradation	NEff = 1.0
Damp heat	1000 hrs, 85C/85% RH	unprotected cell <3% degradation	NEff > 0.97
High Temperature Soak	Unbiased soak at 180°C, 200°C, 225°C and 250°C	<0.5% degradation after 25 yr equiv lifetime	Neff = 1.0
Outdoor Field Trial	> 10 kW on sun For 6 months	characterization	> 10 kW total
High Temperature Reverse Bias	–0.8V and –1.6V @ 140°C until failure	characterization	NEff = 1.0

Figure 8. C4MJ qualification tests and preliminary results.

isotype standards has been calibrated by PTB and results on the round robin comparison will be presented when they become available and incorporated in the calibration of production testers at Spectrolab.

Figure 8 summarizes the qualification requirements and current test status for the C4MJ technology. High temperature reverse bias (HTRB) was instituted in our qualification requirements for the first time to determine the impact of current mismatch, shadowing or other operating conditions that may result in a cell being reverse biased for extended periods. All cells were able to withstand the equivalent of 25% operating lifetime reverse biased with twice the diode turn-on voltage at 110°C.

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 over 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 [18]. The data reflect little or no degradation over the test interval (i.e., any degradation is within the error bounds of the measurements).

Outdoor testing was added to our internally imposed qualification requirements for the first time for the C4MJ technology, to reinforce the various indoor accelerated tests with actual on-sun experience with the metamorphic technology, with a statistically significant sample. We are currently engaged in conducting a field test with over 10 kW on sun, in cooperation with a CPV system supplier, to provide some real world experience and data prior to first production.

FUTURE DIRECTIONS

Over the medium to long term, we expect to introduce improvements to the fundamental epitaxial structures used in multijunction devices, as illustrated in the device structure roadmap of Figure 9. 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. Given that the current record performance is still held by a lattice-matched device, it seems quite possible to see future lattice-matched production cells with higher efficiency than the C4MJ technology.

Other upright metamorphic improvements are envisioned, including three-junction cells with greater lattice mismatch to obtain top and middle cell band gaps closer to the theoretical maximum. Progress indevice quality and repeatability for lattice-matched 4, 5, and 6 junction cells will be directly transferrable (or nearly so) to upright metamorphic cells. Several other promising research vectors exist for higher efficiency cells as well, including inverted metamorphic technology [19,20], as well as semiconductor bonding approaches [21]. The high quality of today's production multijunction cells, and the high performance laboratory demonstrations that have recently been reported in each of these areas, suggest that continuing rapid progress in cell efficiency is likely, and as a result, CPV systems will continue to improve in the cost of electricity delivered and in efficiency of land use.

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.Those investments have been leveraged by the funding of the US Department of Energy Solar Energy Technology Program to achieve an almost 10% relative efficiency gain combined with substantial cost reductions for CPV cells over the past 3 years. With continued R&D, there is every reason to believe similar gains can be achieved in the coming years.

REFERENCES

[1] Kamath et al, "Large-Area High-Efficiency (AlGa)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.

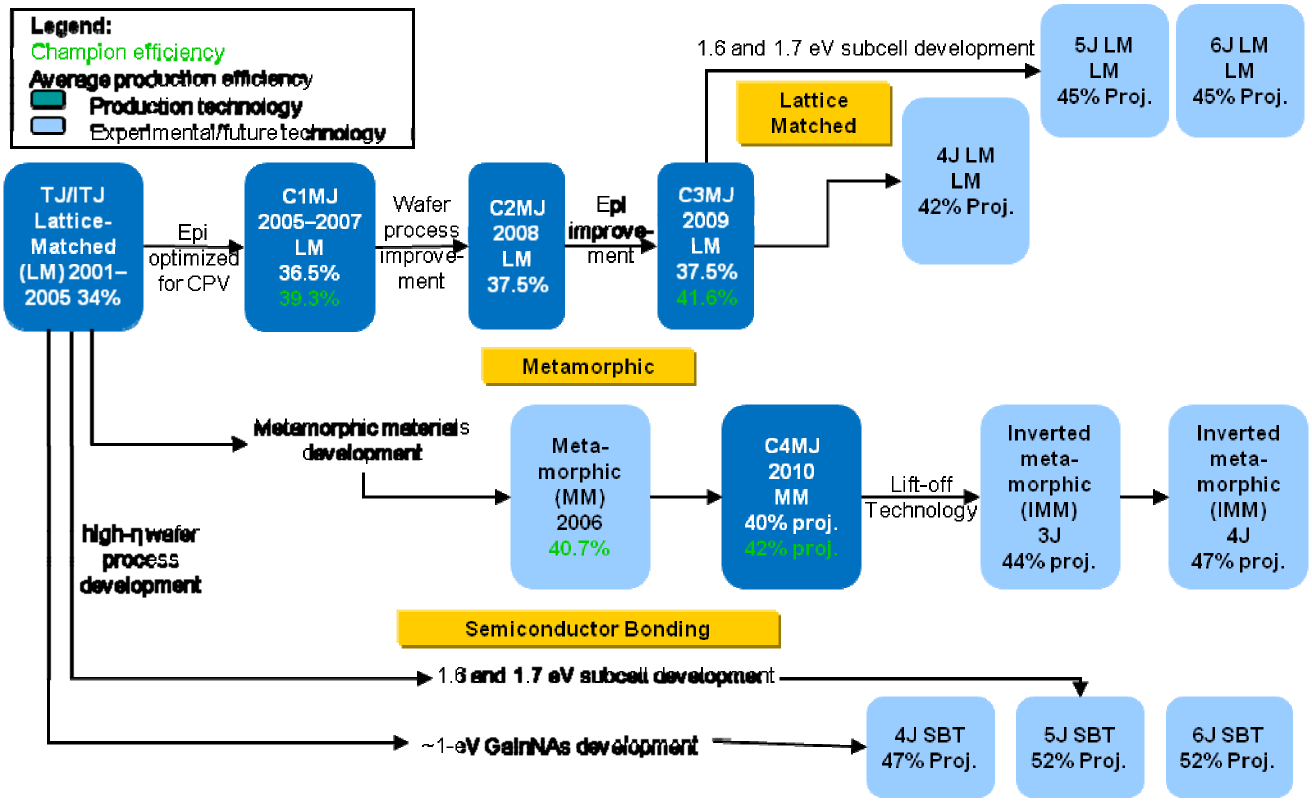


Figure 9. Multiple research approaches for multijunction cells to achieve 50% efficiency and beyond.

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

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

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

[11] 41.6% record efficiency cell

[12] 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.

[13] King et al, "40% efficient metamorphic GaInP/GaInAs/Ge multijunction solar cells," *Applied Physics Letters*, Vol 90 No. 183516, 2007

[14] Dimroth et al, "Metamorphic Gainp/Gainas/Ge Triple-Junction Solar Cells With > 41 % Efficiency," *IEEE 34th Photovoltaics Specialists Conference*, Philadelphia, Pennsylvania, June 2009.

[15] King et al, "New Horizons in III-V Multijunction Terrestrial Concentrator Cell Research," *Proceedings of the 21st European PV Solar Energy Conference*, Dresden, Germany, (WIP-Renewable Energies, Munich), 2006.

[16] Jones et al, "Progress In High-Efficiency Terrestrial Concentrator Solar Cells," *IEEE 34th Photovoltaics*

Specialists Conference, Philadelphia, Pennsylvania, June 2009.

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

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

[19] J, Geisz et al,”40.8% Efficient Inverted Triple-Junction Solar Cell with Two Independently Metamorphic Junctions,” *Applied Physics Letters*, Vol 93 No. 123505, 2008.

[20] Boisvert et al, “Development of Advanced Space Solar Cells at Spectrolab,” *IEEE 35th Photovoltaic Specialists Conference*, Honolulu, Hawaii, 2010.

[21] Law et al, “Semiconductor-Bonded III-V Multijunction Space Solar Cells,” *IEEE 34th Photovoltaic Specialists Conference*, Philadelphia, Pennsylvania, 2009.

---

[i] This work was partially funded by the U.S. Department of Energy under the Solar Energy Technologies Program, Contract .No. DE-FC3607GO17052.