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Preprint

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Presented at the 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion (WCPEC-4)
Waikoloa, Hawaii
May 7–12, 2006

Conference Paper
NREL/CP-520-39791
May 2006

NREL is operated by Midwest Research Institute ● Battelle Contract No. DE-AC36-99-GO10337

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MULTIJUNCTION PHOTOVOLTAIC TECHNOLOGIES FOR HIGH-PERFORMANCE CONCENTRATORS*

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ABSTRACT

Multijunction solar cells provide high-performance technology pathways leading to potentially low-cost electricity generated from concentrated sunlight. The National Center for Photovoltaics at the National Renewable Energy Laboratory has funded different III-V multijunction solar cell technologies and various solar concentration approaches. Within this group of projects, III-V solar cell efficiencies of 41% are close at hand and will likely be reported in these conference proceedings. Companies with well-developed solar concentrator structures foresee installed system costs of \$3/watt—half of today's costs—within the next 2 to 5 years as these high-efficiency photovoltaic technologies are incorporated into their concentrator photovoltaic systems. These technology improvements are timely as new large-scale multi-megawatt markets, appropriate for high performance PV concentrators, open around the world.

INTRODUCTION

Under contract to the U.S. Department of Energy (DOE), the National Center for Photovoltaics (NCPV) at the National Renewable Energy Laboratory (NREL) houses the High-Performance Photovoltaic Project, which supports in-house and subcontracted research in high-performance future-generation photovoltaics (PV), polycrystalline thin-film PV, and multijunction concentrator devices. This paper focuses on the research and development of multijunction III-V solar cells that can be incorporated into structures that track and concentrate sunlight using either mirrors or lenses. The development of these systems—high-performance concentrator PV systems—target the goal of the Solar Program in its Multi-Year Technical Plan, "to develop technology and red-uce market barriers to the point where the cost of solar energy becomes competitive in relevant energy markets—principally in the building and power plant markets" [1]. This Multi-Year Plan provides a good framework to evaluate the significance of the technical progress of multijunction concentrator devices.

The DOE Solar Energy Technologies Program is implementing a program management tool called the Stage Gate approach [1]. The approach reflects the development history of high-efficiency multijunction solar cells. Preliminary investigation begun in the early 1980s on multijunction solar cells proceeded to an exploratory research phase, and then to further development for the satellite power market in the 1990s. Near the turn of the century, further development occurred within the High-Performance PV Project, leading to ongoing validations for use in high-performance solar concentrators. Now, these technologies and systems are approaching commercial launch in their first multi-megawatt power plant projects. Each gate in this technology development represented an evaluation where decisions were made by companies, researchers, and program managers to proceed further with increasing sums of money. With the imminent commercial launch of products, investors are now exploring the feasibility and viability of very large multi-megawatt concentrator PV projects requiring funding 10 to 100 times larger than the early funding of research for III-V multijunction cells. This is a Stage Gate characteristic, that the importance of the gate evaluations becomes greater for the later stages requiring more funding.

The original implementation and goals for the High-Performance PV Project fit nicely within the present program management framework of the DOE Solar Energy Technologies Program and its recently announced Solar America Initiative. As mentioned previously, the High-Performance PV Project goal is consistent with the overall goal of the Solar Program that specifically includes large-scale power plant markets. Table 1 is taken from the recent DOE Solar Energy Technologies Program Plan and summarizes the impact of the high-efficiency solar cells on system costs for a concentrator PV utility reference system [1].

System size	MW	10	12.5	16
Module price	$\$/W_{dc}$	4.13	3	1.56
Cell efficiency	%	26 (Si)	32 (MJ)	40 (MJ)
Module size	kW_{pdc}	40	50	64
Module efficiency	%	20	25	32
Installed system price	$\$/W_{dc}$	5.95	4.3	2.52
LCOE	$\$/kWh_{ac}$	0.15–0.27	0.10–0.15	0.06–0.11

Table 1. Benchmark (10-MW) system parameters and impact of multijunction (MJ) solar cell efficiency on concentrator PV utility reference system, as taken from Table 3.1.6-5 in reference [1].

*This work has been authored by an employee or employees of the Midwest Research Institute under Contract No. DE-AC36-99GO10337 with the U.S. Department of Energy.

The 10-MW system with its benchmarked parameters has a module conversion efficiency of 20% based on today's crystalline-silicon solar cells designed for concentrators and having nominal 26% efficiencies. The 12.5-MW system (25% module efficiency) uses 32% III-V multijunction cell available in quantity today, whereas the 16-MW system costs and 32% module conversion efficiency are based on 40% III-V multijunction cells. The levelized cost of energy (LCOE) for the Phoenix location varies according to financial assumptions, but the impact of higher efficiency on electricity cost is clear: solar cell efficiencies of 41% and higher are worthwhile targets on the pathway to significant market deployment and commercialization of high-performance concentrator PV systems. To give an idea of this technology's availability, the 39% solar cell demonstrated last year by Spectrolab is expected to be easily transferable to production at multi-hundred kW levels. Achieving these targets highlights an advantage of concentrator PV systems when successfully launched commercially beyond their benchmark values: 1 MW at one sun of multijunction solar cells can power 1 GW of concentrator PV systems at 1000 suns. Similarly, 1 GW of multijunction solar cells can power 1 TW of concentrator PV systems, revealing a possible pathway to significant TW-levels of electricity production.

HIGH-PERFORMANCE PHOTOVOLTAICS PROJECT

The High-Performance PV Project has supported several III-V multijunction PV projects that were initially funded for three years beginning in 2003. We have described research results from these projects at earlier conferences, and there are several papers in these proceedings that describe the most recent findings as these projects near completion [2].

In 2003, a rigorous evaluation process identified the highest-quality research proposals most likely to achieve project goals. Seven companies and universities received awards, which are summarized in Table 2 along with two additional subcontracts. The additional subcontracts were directed to SunPower Corporation for low-concentration, high-efficiency Si modules and to Underwriters Laboratories (originally awarded to Arizona State University) for qualifications standards to support industry's product development for commercial launch.

A second University of Delaware subcontract was selected competitively in a separate PV Exploratory Research project solicitation and is described in another High-Performance PV contribution to this conference. That project explores third-generation PV approaches for achieving over 50%-efficient solar cells. NREL in-house researchers are also developing III-V multijunction and other third-generation PV technologies. Technical collaboration and coordination of the subcontract projects with the NREL in-house research takes many forms, including measurements and characterization of materials and devices, cooperative R&D agreements, joint publications, site visits, and joint participation in related projects such as the recent DARPA project for 50% solar devices described in a separate presentation at this conference.

III-V MULTIJUNCTION SOLAR CELL R&D

Several III-V multijunction solar cell structures have been developed and demonstrated under the High-Performance PV Project, but some still need further exploration to achieve even higher efficiencies. The device R&D focus is on the materials, device design, antireflective coating, and the spectrum. Several of these novel devices will be described below.

Subcontract	**Title**
Spectrolab, Inc.	Ultra-High-Efficiency Multijunction Cell and Receiver Module
California Institute of Technology	Four-Junction Solar Cell with 40% Target Efficiency Fabricated by Wafer Bonding and Layer Transfer
University of Delaware	Novel High Efficiency PV Devices Based on the III-N Material System
OHIO STATE	Optimized III-V Multijunction Concentrator Solar Cells on Patterned Si and Ge Substrates
AMONIX	Design and Demonstration of a Greater than 33% Efficiency High-Concentration Module Using over 40% III-V Multijunction Devices
JX Crystals	Toward 40%-Efficient Hybrid Multijunction III-V Terrestrial Concentrator Cells
Concentrating Technologies, LLC	A Scaleable Reflective Optics High Concentration PV System
SunPower Corporation	Low Concentration PV System Prototype Assessment of a 3x Mirror Module with SunPower's 20% Efficient A-300 Solar Cell
Underwriters Laboratories	Development of IEC Design Qualification Standard for Concentrator PV Modules

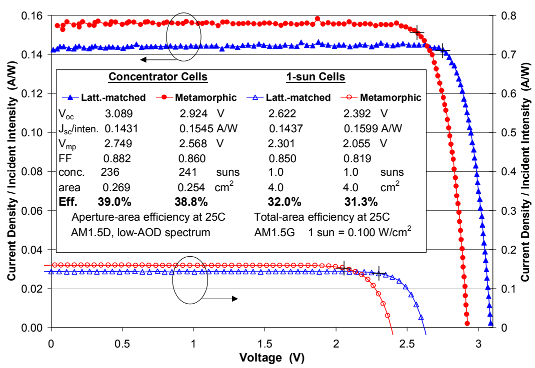
Table 2. Concentrator PV subcontracts funded by the DOE/NREL High-Performance PV Project. Most of these subcontracts end in 2007. The Solar America Initiative in 2007 offers an opportunity for concentrator PV technologies to move beyond the High Performance PV Project phase.

The high-efficiency cell development work at Spectrolab builds on the successes it had with producing record-efficiency 3-junction (3J) GaInP / GaInAs / Ge solar cells of both lattice-matched and lattice-mismatched (metamorphic) designs.

The metamorphic approach achieves the desired subcell bandgaps with compositions that are lattice-mismatched to the growth substrate, such as 2%-In to 35%-In GaInAs and GaInP compositions with the same lattice constants, while minimizing the dislocations that typically come with lattice-mismatched growth. The bandgap can also be engineered in some materials by tailoring the ordering of elements from the same column of the Periodic Table within the crystal lattice—for instance, Ga and In ordering on the Group-III sublattice in GaInP.

Figure 1 plots the light current-voltage (I-V) curves for recent record-efficiency concentrator cells, with 39.0% for a lattice-matched design and with 38.8% for a metamorphic design, essentially reaching parity with lattice-matched cells. The 39.0% result achieved in this program was the highest conversion efficiency yet measured and independently confirmed in 2005 for any PV device; higher efficiencies are expected this year [3].

Fig. 1. World-record concentrator solar cell efficiencies achieved last year by Spectrolab.



Also last year, the NREL III-V Multijunction group recently developed an ultra-thin, inverted, lattice-mismatched GaInP / GaAs / GaInAs solar cell technology. The cell was designed for one-sun applications, but had top-surface grid metallizations that allowed testing at low concentration ratios. The cell showed peak performance for ~5–10 suns concentration, yielding a conversion efficiency of 37.9% at 10.1 suns. At the time, the measurement constituted a new world record that, however, only lasted about a month in this fast-moving arena of research. It is expected that an improved version of this device will soon be demonstrated with efficiencies greater than 40% at concentrations of about 100 suns [4].

California Institute of Technology, under its subcontract, is developing a 4-junction solar cell with 40% target efficiency fabricated by wafer bonding and layer transfer. To accomplish this, Cal Tech uses wafer-scale synthesis of InP / Si, Ge / Si, and GaAs / Si on transferred epitaxial template films by layer-transfer fabrication; secondly, they grow high-quality epitaxial compound semiconductor 2-junction subcells and double-heterostructures (InGaP / GaAs / Ge / Si and InGaAsP / InGaAs / InP / Si) on transferred epitaxial template layers. Recent results include wafer-scale layer transfer of Ge / Si and InP / Si template layers at the 50-mm wafer diameter, with less than 1 nm roughness and less than 0.1 ohm-cm^2 interface resistance. They have fabricated active GaInP and GaAs double-heterostructures with about $10^7/cm^2$defects on Ge / Si templates

The University of Delaware, under its subcontract, focuses on demonstrating high-performance tandem solar cells based on the InGaN material system. Although the high-bandgap InGaN alloys are used in commercial light-emitting diodes, there are many unknowns for the low-bandgap In-rich alloys. The approach is to develop high-bandgap In-lean InGaN solar cells and identify growth techniques and buffer layers for low-bandgap In-rich InGaN grown on Ge to improve the understanding of this portion of the alloy range. Early results include demonstrating GaN solar cells with external quantum efficiencies of >10% when measured through metal Au contact; InGaN solar cells with 7% In that show V_{oc} = 2 V, dominated by a radiative defect channel; and growth of InN demonstrated on Ge, with AlN and Al as buffers.

Ohio State, with MIT as a subtier contractor, has been developing and demonstrating the use of novel 3-D substrate engineering in Si and Ge to grow III-V multijunction devices on Si or Ge. The researchers demonstrated unprecedented, near-ideal structural perfection for a double-junction cell grown on Si using SiGe that successfully avoided all mismatch-related defects, such as threading dislocations and anti-phase domains.

As mentioned previously, under another NREL subcontract for Future Generation PV technologies, the University of Delaware is analyzing advanced solar cell efficiency approaches such as multiple-energy-level quantum dot solar cells, which include realistic loss mechanisms, to identify solar designs that have a credible potential for >50% efficiency.

A quantum-dot group from NREL's Basic Sciences Center demonstrated quantum yields last year of up to 300%, corresponding to three electron-hole pairs per photon at photon energies four times the quantum-dot bandgap [4]. This discovery may enable more efficient use of high-energy photons in the solar spectrum, once these materials are incorporated into a device design.

CONCENTRATOR SYSTEMS R&D

Several concentrator systems are being developed and have been demonstrated under the High-Performance PV Project, but they still need further exploration. Emphasis on the receiver package focuses on the receiver and system size, mounting and interconnects, active vs. passive cooling, and reliability and degradation. These subcontracts are described below.

Amonix Corporation currently markets large-scale units, 35 kW in size, and is deploying power plant systems through a joint venture in Spain following earlier large system installations in U.S. utility grids. Under its subcontract, Amonix Corp. has been designing and fabricating a lens-cell element that will use >40%-efficient multijunction solar cells. Amonix envisions that such a solar device will be 33% efficient.

The design of a Fresnel lens concentrator system must account for several optics issues, including nonuniformity, chromatic aberration, lens absorption, and matching to multijunction solar cell response. Based on their new optical design, Amonix engineers recently tested a lens-cell element that reached an efficiency of 28.2% at operating temperature and on-sun, not in the laboratory.

JX Crystals, under its subcontract, has focused on demonstrating a 40%-efficient hybrid InGaP / GaAs-GaSb multijunction cell combination in a 33%-efficient Cassegrainian PV concentrator panel. They have designed and fabricated all module components, including two cell packages, three optical components, and two cooling components for incorporation into their 25-cm x 25-cm dichroic Cassegrain module.

Concentrating Technologies, LLC, has been demonstrating a reflective-optics concentrator system using passively cooled Spectrolab triple-junction cells at 500x. Results include the continuous operation of Spectrolab triple-junction-powered units for more than one year. As a system test, the most significant accomplishment came from improvements to their power-conditioning unit interfacing with the Arizona Public Service grid. The architecture of the Concentrating Technologies module is versatile and allows next-generation solar cells as a “drop in” replacement or upgrade.

Sunpower Corporation, in collaboration with JX Crystals, has completed its work focusing on low-concentration flat-plate designs using high-efficiency silicon cells. With this design, the impact is anticipated to be modules at $1.50/watt, instead of today’s $3/watt. The advantages to this approach are the ability to compete in the PV rooftop market and no need for a solar tracker.

An important challenge for concentrating PV (CPV) systems is reliability since systems are just beginning to enter the market. CPV needs to be reliable so that customers will trust the technology and be willing to buy into it. Qualification standards provide a series of accelerated and stress tests meant to identify system weaknesses before products are deployed, thereby providing a measure of assurance to both customers and sellers of long-term system reliability. In 2001, IEEE qualification standards were completed for CPV, and international standards are on the way under the aegis of the International Electrotechnical Commission. Under a subcontract originally started with Arizona State University, Underwriters Laboratories is working to develop, coordinate, and publish an IEC standard for the design qualification of CPV modules. The first international qualifications standard for CPV systems was submitted earlier this year for international ballot.

CONCLUSIONS

Theoretical efficiencies are still much higher than laboratory multijunction efficiencies. And researchers are designing approaches for solar cells with efficiencies greater than 50%, while solar cells with 41% efficiency are likely to be available imminently in large quantities. The impact of high performance on cost of electricity generated by solar concentrators is expected to be significant—specifically, achieving a system price of $\$2.00/W_p$ and less for CPV systems with 41%-efficient III-V multijunction solar cells.

Progress toward achieving long-term DOE goals is highlighted by the reported advances of high-efficiency cells, as well as by advances in concentrator modules demonstrating improved reliability and, finally, the appearance of large multi-megawatt CPV projects in the marketplace. The High-Performance PV Project has been focused to ensure that III-V multijunction concentrators reach efficiency levels consistent with cost-competitive goals and capture a large portion of a significant energy market. Utilities around the world are already beginning to see concentrator PV as a future energy alternative, one capable of meeting terawatts of future electricity production.

ACKNOWLEDGEMENTS

This work is supported under DOE Contract No. DE-AC36-99GO10337 with NREL. Many people in both organizations have contributed to the development and implementation of the High-Performance PV Project. The authors thank the NREL High-Performance III-V Multijunction Concentrator Group and all of the High-Performance PV subcontractors.

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