DOE High Performance Concentrator PV Project

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ABSTRACT

Much in demand are next-generation photovoltaic (PV) technologies that can be used economically to make a large-scale impact on world electricity production. The U.S. Department of Energy (DOE) initiated the High-Performance Photovoltaic (HiPerf PV) Project to substantially increase the viability of PV for cost-competitive applications so that PV can contribute significantly to both our energy supply and environment. To accomplish such results, the National Center for Photovoltaics (NCPV) directs in-house and subcontracted research in high-performance polycrystalline thin-film and multijunction concentrator devices with the goal of enabling progress of high-efficiency technologies toward commercial-prototype products. We will describe the details of the subcontractor and in-house progress in exploring and accelerating pathways of III-V multijunction concentrator solar cells and systems toward their long-term goals. By 2020, we anticipate that this project will have demonstrated 33% system efficiency and a system price of \$1.00/W_p for concentrator PV systems using III-V multijunction solar cells with efficiencies over 41%.

1 Introduction

The High-Performance (HiPerf) PV Project seeks to explore the ultimate performance limits of existing PV technologies, approximately doubling their sunlight-to-electricity conversion efficiencies during its course, to accelerate and enhance their impact in the marketplace. Along with other criteria for success (such as module manufacturing cost and reliability, which are central to other components of the DOE National PV Program), module sunlight-to-electricity conversion efficiency is a key parameter driving the economics of PV-generated electricity. Simply put, raising conversion efficiency reduces cost per unit of electrical output.

Solar-electric concentrator technologies are rapidly moving into energy markets around the world, and concentrator photovoltaics (CPV) companies are developing even better products using III-V solar cells with efficiencies of 37% and higher. This paper will describe progress on exploring critical pathways for a PV technology having high potential to reach cost-competitiveness goals and to gain a bigger piece of the market worldwide. By 2020, we anticipate this project will have demonstrated 33% system efficiency and a system price of \$1.00/W_p for CPV systems using III-V multijunction solar cells with efficiencies over 41% [1].

2 Approach

The NCPV at the National Renewable Energy Laboratory (NREL), under contract to the DOE, directs in-house and subcontracted research in high-performance polycrystalline thin-film and multijunction concentrator devices. This paper focuses on the multijunction concentrator research and development. The project's approach pursues research toward established goals through extensive collaboration so as to produce significant contributions for the entire PV industry. A roadmap of the HiPerf PV Project approach is shown for about the next decade (Fig. 1).

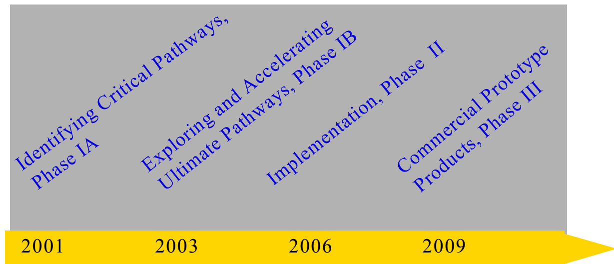

Figure 1. Roadmap of the High-Performance PV Project

The project consists of three phases that focus on a specific approach to solving the challenges associated with high efficiencies. The second HiPerf PV subcontract solicitation was recently completed; it allows the NCPV to provide three years of funding to the top-ranked companies and universities. The first phase is critical as it provides a means to accelerating toward the most-promising paths for implementation, followed by commercial-prototype products.

Seven companies and universities were selected competitively and have received awards for the HiPerf PV Phase IB of the III-V Multijunction Concentrators (Table I). Additional subcontracts were directed to SunPower Corporation for low-concentration Si toward high efficiency and to Arizona State University for reliability work. A second subcontract to the University of Delaware, originally selected competitively in a PV Exploratory Research project solicitation, became part of the HiPerf PV Project as the result of a NREL PV project reorganization.

3 Project Goals

To address the HiPerf PV R&D long-term goals of bringing III-V multijunction solar cells and modules toward 41% and 33% efficiencies, respectively, the project investigates a wide range of complex issues and provides initial modeling and baseline experiments of several advanced concepts. This addresses one of the highest-priority goals for applied research in the U.S. Photovoltaics Industry Roadmap [2]: "...developing new materials that push current technologies to the next performance level, discovering and demonstrating new devices with ultra-high efficiencies...and developing devices with ultra-low costs."

Table I: Subcontract projects under the HiPerf PV's "Exploring and Accelerating Ultimate Pathways"

Subcontractor	Title
Amonix	Design and Demonstration of a Greater than 33% Efficiency High-Concentration Module Using over 40% III-V Multijunction Devices
Arizona State University	Development of IEC Design Qualification Standard for Concentrator PV Modules
California Institute of Technology	Four-Junction Solar Cell with 40% Target Efficiency Fabricated by Wafer Bonding and Layer Transfer
Concentrating Technologies, LLC	A Scaleable Reflective Optics High Concentration PV System
University of Delaware	Novel High Efficiency PV Devices Based on the III-N Material System
University of Delaware	Theoretical and Experimental Investigation of Approaches to >50% Efficient Solar Cells
JX Crystals	Toward 40%-Efficient Hybrid Multijunction III-V Terrestrial Concentrator Cells
Ohio State	Optimized III-V Multijunction Concentrator Solar Cells on Patterned Si and Ge Substrates
Spectrolab, Inc.	Ultra-High-Efficiency Multijunction Cell and Receiver Module
SunPower Corporation	Low Concentration PV System Prototype Assessment of a 3x Mirror Module with SunPower's 20% Efficient A-300 Solar Cell

4 III-V Multijunction Solar Cell R&D

Several III-V multijunction solar cell structures have been developed and demonstrated under the HiPerf PV Project, but they still need further exploration. 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.

A quantum-dot group from NREL's Basic Sciences Center recently demonstrated quantum yields of up to 300%, corresponding to three electron-hole pairs per photon at photon energies four times the quantum-dot bandgap [3]. This discovery may enable more efficient use of high-energy photons in the solar spectrum.

Spectrolab, Inc., under a HiPerf PV subcontract, aims to develop ultra-high-efficiency triple-junction solar cells and demonstrate a working robust receiver package. They have achieved an efficiency of 37.3% efficiency for a 3-junction terrestrial concentrator cell [4]. The 3-junction GaInP/GaInAs/Ge concentrator solar cells were grown on a Ge substrate incorporating epitaxial device features to optimize performance under the concentrated terrestrial spectrum. The cells were processed at Boeing Spectrolab. The cell efficiency was measured at NREL at 37.3% at 175 suns under the AM1.5 Direct, low-AOD spectrum, which is the standard reporting spectrum for the HiPerf PV Program (17.5 W/cm^2, 25°C). The 37.3%-efficient concentrator cell aperture area is 0.264 cm^2, with a metallization grid coverage optimized for 120 suns (see Fig. 2).

For the receiver package, the focus is on analytical modeling and long-term experimental evaluation of different receiver designs. To date, they have demonstrated reliability of concentrator cell receivers for more than one year.

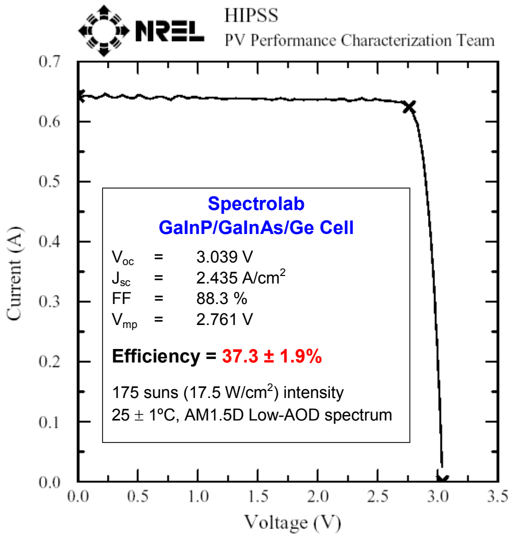

Figure 2. Efficiency vs. concentration measured at NREL for a Boeing-Spectrolab GaInP/GaInAs/Ge tandem cell. This cell measured 37.3% at 175 suns.

California Institute of Technology, under a HiPerf PV 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 at the 50-mm wafer diameter, polish-free removal of surface damage to prepare templates for epitaxial growth, and control of stress and thermal cyclability in Ge/Si substrates [5].

Ohio State, under a HiPerf PV subcontract, is developing and demonstrating the use of novel 3-D substrate engineering in Si and Ge to achieve spectrum-optimized bandgap profiles leading to >40% III-V multijunction concentrators on Si or Ge. They have recently "tuned" lattice-constant Si substrates for ideal III-V growth on Si [6]. This result was achieved by using $Si_{0.04}Ge_{0.96}$ termination. Additionally, they successfully grew GaAs on tuned (optimum) Si lattice substrates by optimizing nucleation on mixed SiGe surfaces. Optimizing the upper SiGe grade reduced Ge/SiGe/Si substrate dislocation density to a record 6×10^5 cm^{-2}, and they succeeded in GaAs growth on patterned SiGe and Ge.

The University of Delaware, under a HiPerf PV subcontract, focuses on demonstrating high-performance tandem solar cells based on the InGaN material system [7]. The approach is with high-bandgap GaN and In-lean InGaN p-i-n and quantum well solar cells, and with low-bandgap In-rich InGaN grown on Ge.

Recent 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 radiative defect channel; and growth of InN demonstrated on Ge, with AlN and Al as a buffer (see Fig. 3).

Under another NREL subcontract, 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 determine solar designs having credible potential for >50% efficiency [8].

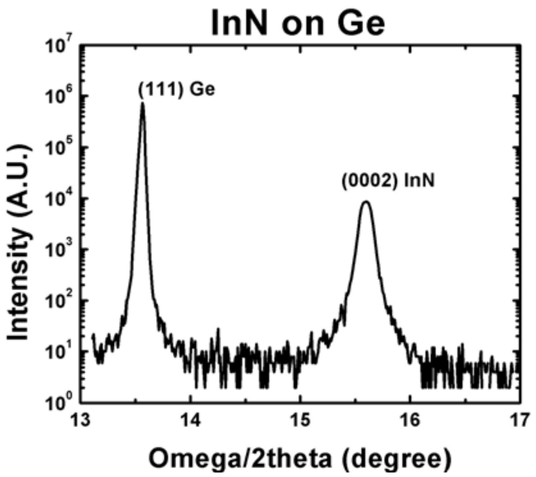

Figure 3. Intensity vs. omega//2theta, demonstrating growth of InN on Ge at the University of Delaware

JX Crystals, under a HPerf PV subcontract, focuses on demonstrating a 40%-efficient hybrid InGaP/GaAs-GaSb multijunction cell in a 33%-efficient Cassegrainian PV concentrator panel (see Fig. 4). Recently, they demonstrated a 30%-efficient InGaP/GaAs 2-junction cell and an 8%-efficient GaSb infrared cell for incorporation into their 25-cm x 25-cm dichroic Cassegrain module [9].

Sunpower Corporation, under a HiPerf PV subcontract, is focusing on low-concentration flat-plate module designs using high-efficiency silicon cells [10]. 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.

5 Concentrator Module R&D

Several concentrator modules are being developed and have been demonstrated under the HiPerf 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.

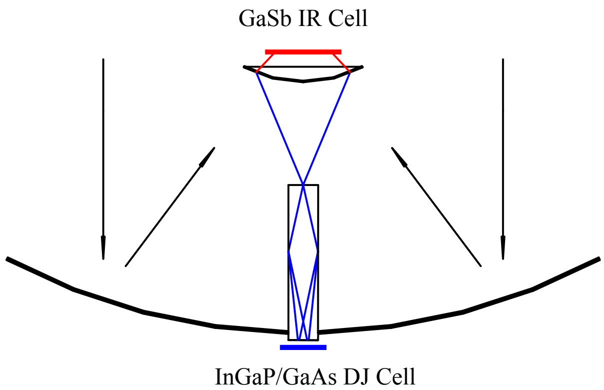

Figure 4. JX Crystals Inc.'s Cassegrain PV concentrator module with dichroic secondary optics separating the solar infrared from the visible spectrum

Amonix Corporation currently focuses on large-scale modules (see Fig. 5). Under the HiPerf PV Project, Amonix Corp. is designing and fabricating a module that will use >40%-efficient multijunction solar cells. Amonix envisions that such a module will be 33% efficient. The approach includes: designing packing for the Ge-substrate-based multijunction solar cells, testing packaged cells under a Fresnel lens, characterizing different cells / package / lens configuration, and designing and constructing 33%-efficient modules, to be tested on-sun, not in the laboratory.

Figure 5. Amonix Inc.'s high-performance concentrator modules in an Arizona Public Service Solar Power Plant. For scale, note white pickup truck beneath the module.

Significant results include studying the optics. Design of a Fresnel lens concentrator suystem must account for several optics issues, including nonuniformity, chromatic aberration, lens absorption, and matching to multijunction solar cell response. The top cell is identified as the significant efficiency-limiting aspect of the current design, and Amonix redesigned the optics with a yield of >26% lens/cell efficiency (without external cooling).

Amonix sees a major impact on the industry with the successful commercialization of modules exceeding 33%. They expect a paradigm shift in installed system cost and a leap into new PV market ideally suited for PV concentrators [11].

Concentrating Technologies, LLC, under the HiPerf PV Project, focuses on demonstrating a 33%-efficient reflective-optics concentrator module using passively cooled Spectrolab triple-junction cells at 500x (see Fig. 6). Results include the continuous operation of Spectrolab triple-junction-powered units in continuous operation for more than one year, more than 14 W/cm^2 from the 2.25-cm^2 cell has been demonstrated, and 500x passive cooling with cell temperatures only slightly above flat-plate norms [12].

The architecture of the Concentrating Technologies module is versatile and allows next-generation solar cells as a "drop in" replacement or upgrade.

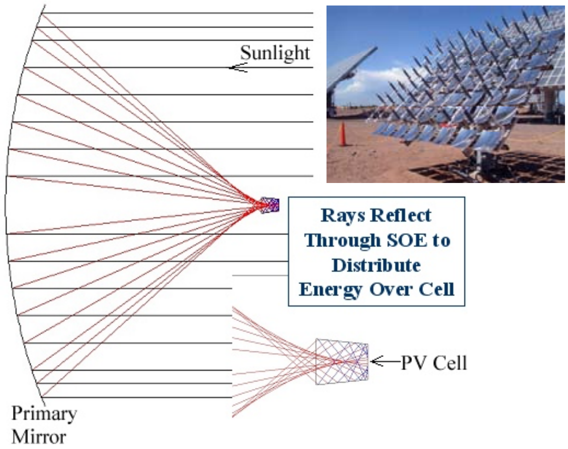

Figure 6. Concentrating Technologies, LLC, reflective concentrator module approach. The sketch portrays the optics design, and the inset photo shows the 1-kW module with its mirrors and passive heat-dissipation elements. This unit is under test at an Arizona Public Service facility.

6 Standards & Reliability

An important challenge for CPV is reliability. CPV needs to be reliable so that utilities will trust the technology and be willing to buy into it. In 2001, IEEE qualification standards were completed for CPV, and international standards are on the way.

Arizona State University, under a HiPerf PV subcontract, is working to develop, coordinate, and publish an IEC standard for the design qualification of CPV modules. Their approach is to contact CPV users and manufacturers to identify the CPV module qualification requirements, work with the IEC / TC82 / WG7 committee to improve draft versions, validate the new procedures agreed by WG7, and submit the draft standard to IEC for official circulation, comments, and voting. To date, they have adopted side-by-side I-V and dark I-V measurement procedures by WG7 (verified at ASU), included explicitly reflective CPV, and discussed a concept of "smaller representative samples"; modification/adoption is under way in the next draft [13].

7 Conclusions

Phase IB, "Exploring and Accelerating Ultimate Pathways," of the HiPerf PV Project is under way, with in-house and subcontracted research efforts in III-V multijunction concentrators.

Theoretical efficiencies are still much higher than laboratory multijunction efficiencies. But researchers are involved in designing approaches for solar cells with efficiencies >50%, that can be produced in quantity within 5 years. The impact of high performance on the cost of electricity generated by solar concentrators is expected to be significant—specifically, achieving a system price of \$1.00/W$_p$ for CPV systems with III-V multijunction solar cells having efficiencies over 41%.

Progress toward achieving long-term DOE goals is highlighted by the reported advances of high-efficiency cells, as well as by advances in modules and improved reliability. The HiPerf PV Project is 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 are already beginning to see concentrator PV as a future energy alternative.

8 Acknowledgements

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9 References

[1] S. Kurtz et al., "Recent Progress and Future Potential for Concentrating Photovoltaic Power Systems," *World Renewable Energy Congress.* September 1, 2004, Denver, CO.

[2] *Our Solar Power Future—The U.S. Photovoltaics Industry Roadmap Through 2030 and Beyond,* SEIA, September 2004, 16pp.

[3] R. Ellingson et al., "Highly Efficient Multiple Exciton Generation in Colloidal PbSe and PbS Quantum Dots," *Nano Lett.* **5**, 865-871, 2005.

[4] R.R. King et al., "Metamorphic III-V Materials, Sublattice Disorder, and Multijunction Solar Cell Approaches with over 37% Efficiency," *Proc. 19th European Photovoltaic Solar Energy Conference*, Paris, 2004.

[5] H. Atwater et al., "Ultrahigh Efficiency Microconcentrator PV," 3rd International Conference on Solar Concentrators for the Generation of Electricity or Hydrogen, Scottsdale, AZ, 2005.

[6] S.A. Ringel et al., "Multijunction III-V Photovoltaics on Lattice-Engineered Si Substrates," 31st IEEE PV Specialists Conference, Lake Buena Vista, FL, 2005.

[7] O. Jani et al., "Characterization and Analysis of InGaN Photovoltaic Devices," 31st IEEE PV Specialists Conference, Lake Buena Vista, FL, 2005.

[8] M.Y. Levy et al., "Quantum Dot Intermediate Band Solar Cell Material Systems with Negligible Valence Band Offsets," 31st IEEE PV Specialists Conference, Lake Buena Vista, FL, 2005.

[9] L.M. Fraas et al., "Toward 40% and Higher Solar Cells in a New Cassegrainian PV Module," 31st IEEE PV Specialists Conference, Lake Buena Vista, FL, 2005.

[10] L. Fraas et al., "Efficient Solar Photovoltaic Mirror Modules for Half the Cost of Today's Planar Modules," 3rd International Conference on Solar Concentrators for the Generation of Electricity or Hydrogen, Scottsdale, AZ, 2005.

[11] V. Garboushian, "Marketing Concentrating Solar Systems—Challenges and Opportunities," 3rd International Conference on Solar Concentrators for the Generation of Electricity or Hydrogen, Scottsdale, AZ, 2005.
[12] R.A. Sherif et al., "First Demonstration of Multi-Junction Receivers in a Grid-Connected Concentrator Module," 31st IEEE PV Specialists Conference, Lake Buena Vista, FL, 2005.
[13] R. McConnell et al., "Representative Samples for Concentrator Photovoltaic Module Qualification Testing," 3rd International Conference on Solar Concentrators for the Generation of Electricity or Hydrogen, Scottsdale, AZ, 2005.