

Final Scientific and Technical Report

Project Title: **Transfer Printed Microcells with Micro-Optic Concentrators for Low Cost, High Performance Photovoltaic Modules**

Covering Period: February 1, 2008 to January 31, 2011

Date of Report: April 30, 2011

Recipient: The Board of Trustees of the University of Illinois
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Award Number: DE-FG36-08GO18021

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Cost-Sharing Partners: Semprius Corporation

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Executive Summary: This program of work established and validated a new form factor and fully scalable manufacturing processes for low cost, high performance photovoltaic modules. The programmatic highlights of the work include cost-effective assembly of modules fabricated from single crystalline semiconductor inks by high-throughput transfer printing of the micro-cells, advanced methods of systems level integration of sparse arrays, and design and fabrication of micro optical concentrator arrays that provide significant collection efficiencies of light and high performance of the system when integrated with the PV array module. The designs further provide efficient but fully passive heat management that simplifies fabrication while further enhancing operating capabilities of the modules. This collaborative program of research carried out under this award has exceeded all key guidelines laid out in the original proposal. It first has provided a new means to utilize high performance semiconductor materials in an exceptionally low cost and robust form factor. The technology so engendered by these key materials discoveries, new means of manufacturing, and advanced systems level designs are establishing new benchmarks for reductions in the installed cost/kWh relative to any commercial photovoltaic (PV) energy technology currently in use. The work in this program, having surpassed its key scientific milestones, has gone further and with our partners has now fully validated designs with scalable manufacturing methods for photovoltaic modules that use large-scale arrays of high efficiency solar microcells created from bulk wafers, integrating them in diverse spatial layouts on foreign substrates by transfer printing. Full research modules installed and operating at a utility site since 2010 have established the designs to be a viable PV technology.

Summary of Technical Progress

There has been significant progress made across all programmatic goals described in the plan of work for this award. In general terms, and as noted in the most recent reporting period, the progress in all areas of the effort advanced far ahead of projected time schedules. As of this report all programmatic goals have been met and many substantially exceeded. The rapid pace of our progress engendered as a result opportunities to explore complimentary approaches that might serve as disruptive/synergistic technology approaches to the technology centric goals of this program. The efforts undertaken within the University centered activities of the project have been described in several published papers that have appeared over the term of this award. The manufacturing and module development efforts were carried out at Semprius. These aspects of the project, which involve, in part important forms of proprietary information, are discussed in broader terms several publications, with the Principle Investigator being available to discuss this aspect of the progress more fully with DOE program officers. The relevant publications from UIUC and Semprius are summarized below along with specific patent awards granted to UIUC.

Comparison of Goals and Objectives with Realized Accomplishments.

As noted in the Executive Summary, all programmatic were exceeded during this program of work. The realization of fully validated commercial scale technology most strongly evidences the scope of the advances made. To highlight this progress, we present below a statement of the original project goals, summarizing the progress made against them, and follow that with an overview of the technical progress made at Semprius to realize and commercialize a technology platform embedding the key design, processing, and materials advances made at UIUC.

The key project tasks are summarized in Table 1.

Key Project Tasks	Technical Objectives
Micro transfer printed (μ TP), large area arrays of microcells (μ -cells)	<ul style="list-style-type: none"> • Determine the optimal size and layouts of the GaAs μ-cells, using interconnects, concentrators and thermal management as key metrics • Demonstrate the multistack concepts for creating large quantities of GaAs μ-cells, including the multilayer deposition and low cost processing to define and release the stacked μ-cells • Demonstrate massively parallel, high yield transfer printing of μ-cells
Interconnects	<ul style="list-style-type: none"> • Develop direct ink writing (DIW) for large area, low cost patterning
Micro-optic (μ -optic) concentrators	<ul style="list-style-type: none"> • Implement soft embossing techniques and materials optimized for μ-optic arrays in telecom systems
Heat sinks	<ul style="list-style-type: none"> • Evaluate options, down-select and optimize the shape of the electrical interconnects, the μ-cells and the substrate material to maximize the efficiency of heat extraction.
Fault tolerance/reliability	<ul style="list-style-type: none"> • Build prototypes to demonstrate fault tolerance, yield and reliability
Stacked μ -cells	<ul style="list-style-type: none"> • Conduct a feasibility study on stacked layouts of GaAs and Si μ-cells

In each area, we have exceeded these goals. We specifically have:

- Determined a full design for a high concentration GaAs based microcell module that implements requirements for: thermal management at high concentration levels (1000 Suns and higher); optics for providing such concentration factors; chemistries to form and transfer print high performance PV cells, including dual junction high performance microcells, without degradation of performance; provide massively parallel means to print these advanced PV “inks”; and demonstrate next generation inks including triple junction and multilevel releasable stacks.
- Provided an “ink” chemistry for direct write interconnects as well as developed a parallel route for interconnection based on low cost lithography and screen printing.
- Provided a low cost microconcentrator optic based on embossing as a means of fabrication and developed a significantly higher performance low cost two stage optical design that significantly enhances system level performance while simplifying system level integration.
- Provided a fully scalable design that provides effective, and fully passive, heat management at high concentration levels (1000 suns and higher), exploiting an intrinsically enabling attribute of the microcell design concept.
- Built prototypes to test reliability and eliminate modes of failure leading to the construction and delivery of fully integrated 1 kilowatt systems to demonstrate platform viability at utility scales.
- Demonstrated the feasibility of heterogeneous integration using stacked layouts of PV cells, work progressing in intensive follow on efforts at UIUC and Semprius to provide next generation module design and appropriate high performance PV microcell “inks”.

During the course of this EERE project, Semprius high concentration photovoltaic (HCPV) technology has successfully matured from an early stage research level to a pre-commercialization engineering prototype development level with the successful development and installation of a 1kW HCPV Research Development & Demonstration (RD&D) system. In summary, the technology development is the following: In 2007, Semprius began development of a novel HCPV technology which leverages the micro-transfer printing technology licensed from the University of Illinois at Urbana-Champaign. In 2008, the company fabricated and tested a number of HCPV receivers and proof-of-concept prototypes (comprised of four receivers on a 4” x 4” copper-plated glass backplane with a plano-convex lens array primary optic). In 2009, Semprius developed a high performance dual junctions InGaP/GaAs microcell and developed, fabricated and tested over fifty (50) HCPV module engineering prototypes. Each module has a 14”x14” primary optic containing an 18x18 silicone-on-glass lens array and backplane holding an 18x18 array of InGaP/GaAs-based receivers. Semprius tested individual modules at leading solar test sites in the U.S. and Spain in order to validate the results. The test sites include the NREL, Sandia National Labs, Arizona Public Service, Institute of Concentration Photovoltaics Systems (ISFOC) and the Solar

Energy Institute at the Polytechnic University of Madrid. Semprius also built and deployed a HCPV system, consisting of 32 modules on a 2-axis tracker at our facility in Durham, NC. In 2010, Semprius formed a Joint Development Agreement with Siemens to build and deploy Research Development & Demonstration (RD&D) systems comprised of Semprius HCPV modules and a Siemens-designed 2-axis tracker containing a smart open-loop control system that uses NREL's Solar Positioning Algorithm (SPA). Semprius fabricated and installed a first 1kW HCPV system at Tucson Electric Power using 50 engineering prototype modules and a Siemens tracker.

Key conclusions from R&D for the last three years and current technology status are:

- The micro-transfer printing technology can be successfully used to manufacture high performance micro-cells with no degradation of the quality of transfer printed epi material. The external quantum efficiency and open circuit voltage of transfer printed cells are equal to the performance of cells measured on the source substrate. Yields are high, and the epi substrate can be re-used multiple times with no measurable performance penalty resulting in a significant reduction of the cell fabrication cost.
- A two stage pupil imager optics architecture relying on the use of spherical secondary lenses enables the cost effective fabrication of HCPV modules having large acceptance angle and relaxed alignment tolerances.
- Microcells enable the manufacture of low profile, cost effective HCPV modules with a thermal management solution requiring no heat sink. The microcells deliver optimum performance with reduced series resistance and edge recombination effects cause negligible losses when the microcells are operating under high optical concentration ratios.
- Semprius printable 2-J GaAs/InGaP cells have close world-record efficiency (29% at 1000 suns), the performance of these cells have been independently verified by NREL.
- A 1 kW system has been successfully deployed and its performance is exceeding the customer requirements. Figure 1 presents a picture of the installed system. Since installation in August 2010, the system is performing as expected and has already produced over 1MWh of electricity.

Semprius is now in the process of developing "Alpha" high concentration photovoltaic modules. This second generation module design relies on the fundamental technologies developed during the course of the EERE project. This project has been critically important to Semprius and the company is now successfully leveraging the knowledge and design experience acquired during the build of its first 50 RD&D modules. To meet manufacturing cost targets, the module dimensions and assembly processes are being further refined in order to reduce material expenses and simplify assembly steps. In collaboration with external partners, Semprius is also developing higher efficiency triple junction cells which are of critical importance to further increase the modules power output. These efforts are currently partially supported by a DOE incubator grant managed by NREL.

In addition, Semprius is developing relationships with major Utilities, EPCs and System Integrators who will deploy the modules on two axis trackers in the field and provide a fully integrated photovoltaic system to utility and commercial customers.



Figure 1. Semprius first 1kW HCPV RD&D system installed at Tucson Electric Power in AZ.

Product Identification and Cost Impact Analysis.

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List of publications reporting on work at Semprius supported by this project

- 1 - S. Burroughs et al., "A New Approach For A Low Cost CPV Module Design Utilizing Micro-Transfer Printing Technology", *CPV-6*, April 2010
- 2 - B. Furman et al., "A high concentration photovoltaic module utilizing micro-transfer Printing and surface mount technology", *PVSC*, June 2010
- 3 - K. Ghosal et al., "On-Sun Performance of a Novel Microcell Based HCPV System Located in the Southwest US", *CPV-7*, April 2011

U.S. Patents:

The following awarded US patents cover technology applications of work at Illinois related to applications of printable single crystalline semiconductors in high efficiency devices including photovoltaic modules. The PI can describe confidential filings involving Semprius at the request of the DOE management.

1. US Patent: Nuzzo, R. G.; Rogers, J. A.; Khang, D.-Y.; Ko, H. C.; Lee, K. J.; Mack, K.; Meitl, M. A.; Menard, E.; Sun, Y.; Zhu, Z. 7,799,699, "Printable Semiconductor Structures and Related Methods of Making and Assembling", issued on 07/21/2010.
2. US Patent: Nuzzo, R. G.; Rogers, J. A.; Khang, D.-Y.; Lee, K. J.; Meitl, M.; Menard, E.; Sun, Y.; Zhu, Z. 11/423,192, "Pattern Transfer Printing by Kinetic Control of Adhesion to an Elastomeric Stamp", Notice of Allowance 02/10/2011.
3. US Patent: Rogers, J. A.; Nuzzo, R. G.; Meitl, M. A.; Ko, H. C.; Yoon, J.; Menard, E.; Baca, A. J. 11/858,788, "Release Strategies for Making Transferable Semiconductor Structures, Devices and Device Components", 7,932,123 B2, issued on 04/26/2011.
4. US Patent: Rogers, J. A.; Nuzzo, R. G.; Ahn, B. Y.; Ataman, H.; Baca, A. J.; Choquette, K.; Giannopoulos, A.; Guo, X.; Kasten, A. M.; Ko, H. C.; Meitl, M. A.; Menard, E.; Motala, M. A.; Park, S.; Stoykovich, M.; Yao, J.; Yoon, J.; Yu, C. J., "Optical Systems Fabricated by Printing-Based Assembly", Notice of Allowance 03/09/2011.
5. US Patent: Nuzzo, R. G.; Rogers, J.; Menard, E.; Lee, K.-J.; Khang, D.-Y.; Sun, Y.; Meitl, M.; Zhu, Z. 12/564,566, "Methods and Devices for Fabricating and Assembling Printable Semiconductor Elements", Notice of Allowance 04/07/2011.

UIUC Publications:

1. "Ultrathin silicon solar microcells for semitransparent, mechanically flexible and microconcentrator module designs," J. Yoon, A.J. Baca, S.-I. Park, P. Elvikis, J.B. Geddes III, L. Li, R.H. Kim, J. Xiao, S. Wang, T.H. Kim, M.J. Motala, B.Y. Ahn, E. Duoss, J.A. Lewis, R.G. Nuzzo, P.M. Ferreira, Y.Y. Huang, A. Rockett, and J.A. Rogers, *Nature Materials* 7, 907-915 (**2008**).
2. "Direct-write assembly of flexible, spanning, and stretchable silver microelectrodes for printed electronics," B. Y. Ahn, E. B. Duoss, M. J. Motala, X. Guo, S. I. Park, J. Yoon, R. G. Nuzzo, J. A. Rogers, and J. A. Lewis, *Science* 323, 1590-1593 (**2009**).
3. "Two and Three Dimensional Folding of Thin Film Single-Crystalline Silicon for Photovoltaic Power Applications," Guo, X.; Li, H.; Ahn, B. Y.; Duoss, E. B.; Hsia, J.; Lewis, J. A.; Nuzzo, R. G. *Proc. Nat. Acad. Sci.* 106, 20149-20154, (**2009**).
4. "Compact monocrystalline silicon solar modules with high voltage outputs and mechanically flexible designs," Baca, A. J.; Yu, K. J.; Xiao, J.; Yoon, J.; Ryu, J. H.; Stevenson, D.; Nuzzo, R. G.; Rockett, A. A.; Huang, Y.; Rogers, J. A., *Energy & Environmental Science* **2010**, 3, 208-211.
5. GaAs photovoltaics and optoelectronics using releasable multilayer epitaxial assemblies," Jongseung Yoon, Sungjin Jo, Ik Su Chun, Inhwa Jung, Hoon-Sik Kim, Matthew Meitl, Etienne Menard, Xiuling Li, James J. Coleman, Ungyu Paik, John A. Rogers *Nature* **2010**, 465, 329-333.