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Next Generation Photovoltaic Technologies For High-Performance Remote Power Generation: Final Report

A.L. Lentine, G.N. Nielson, D.S. Riley, M. Okandan, W.C. Sweatt, B.H. Jared, P.J. Resnick, B. Kim, J. Kratochvil, B.J. Anderson, J.L. Cruz-Campa, V.P. Gupta, A. Tauke-Pedretti, J.G. Cederberg, S.M. Paap, C.A. Sánchez, C. Nordquist, M.P. Saavedra, M. Ballance, J. Nguyen, C. Alford, J.S. Nelson; J. Lavin, P. Clews, T. Pluym, J. Wierer, G. Wang, B. Biefeld, W. Luk, I. Brener, J. Granata, B. Aguirre, Mike Haney (University of Delaware), Gautam Agrawal (University of Delaware), and Tian Gu (University of Delaware)

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ABSTRACT

A unique, micro-scale architecture is proposed to create a novel hybrid concentrated photovoltaic system. Micro-scale (sub-millimeter wide), multi-junction cells are attached to a large-area silicon cell backplane (several inches wide) that can optimally collect both direct and diffuse light. By using multi-junction III-V cells, we can get the highest possible efficiency of the direct light input. In addition, by collecting the diffuse light in the large-area silicon cell, we can produce power on cloudy days when the concentrating cells would have minimal output. Through the use of micro-scale cells and lenses, the overall assembly will provide higher efficiency than conventional concentrators and flat plates, while keeping the form factor of a flat plate module. This report describes the hybrid concept, the design of a prototype, including the PV cells and optics, and the experimental results.

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NOMENCLATURE

CPV	Concentrating Photovoltaics
DOE	Department of Energy
LDRD	Laboratory Directed Research and Development
MEPV	Microsystem Enabled Photovoltaics
NREL	National Renewable Energy Laboratory
ONR	Office of Naval Research
PSEL	Photovoltaic Systems Evaluation Laboratory
PV	Photovoltaics
RSEP	Renewable Sustainable Expeditionary Power
SNL	Sandia National Laboratories

EXECUTIVE SUMMARY

Sandia National Laboratories and the University of Delaware proposed a unique, micro-scale architecture to create a novel hybrid concentrated photovoltaic system. Micro-scale (sub-millimeter wide), multi-junction cells are attached to a large-area silicon cell backplane (several inches wide) that can optimally collect both direct and diffuse light. By using multi-junction III-V cells, we can get the highest possible efficiency of the direct light input. In addition, by collecting the diffuse light in the large-area silicon cell, we can produce power on cloudy days when the concentrating cells would have minimal output. Through the use of micro-scale cells and lenses, the overall assembly will provide higher efficiency than conventional concentrators and flat plates, while keeping the form factor of a flat plate module.

The objectives of this project were to build and test a prototype module to demonstrate the enhanced power collection capability of the hybrid CPV concept. Three demonstration units were built and tested at Sandia and the University of Delaware.

We demonstrated key elements of the concept including:

- A large-area silicon cell designed to accept bonded III-V cells. However, gold contamination decreased silicon efficiency to 1-2%
- High-efficiency, micro-scale, dual-junction, III-V (InGaP/GaAs) cells designed to be bonded to the large-area silicon cell, >20% under one-sun and 29% at 200x concentration
- Combined silicon and III-V efficiency of 23% under one-sun, with the output almost entirely from the III-V cell
- Outdoor performance of 20% under real operating conditions for single III-V cells and up to 16% of III-V sub-modules (5 cells in series)
- Bonding of a GaAs wafer to the silicon cell wafer and then releasing the III-V cells from the GaAs substrate
- Series-parallel electrical connection of III-V cells
- Refractive optical lens with 100X concentration fabricated by injection molding
- Measured optical transmission of ~87%%, with projected transmission of 93%

An optical simulation model based upon measured data confirms the hybrid approach has distinct advantages over conventional PV, especially under diffuse light conditions

While we were unable to demonstrate a full functioning prototype due to problems with silicon cell fabrication and III-V cell integration, we believe this project has demonstrated the concepts key to justifying further development.

This report describes the hybrid concept, the design of the prototype, including the PV cells and optics, and the experimental results. A path to resolve the problems that prevented us from demonstrating the full functionality of a prototype module is discussed. Recommendations are made for future work.

1. INTRODUCTION

Motivation

The Renewable Sustainable Expeditionary Power (RSEP) program funded by the Office of Naval Research (ONR) seeks to create a transportable renewable energy system that can provide United States Marines with electricity for a 15-day mission without relying on fuel resupply convoys that often become targets for adversaries. Desired characteristics include:

- Compact form factor to fit on a small Humvee towed trailer (light tactical trailer)
- 3 kW power output
- 40% reduction in fuel usage
- Reduced noise levels
- Deployment and stowage in less than 60 minutes
- Deployable in all terrain types and up to a 15 degree slope
- Accuracy of tracking and ruggedness of system
- 5 kW peak, 2.2 kW average load profile (load profile to be provided by ONR)

To meet these goals, Sandia National Laboratories and the University of Delaware proposed a photovoltaic (PV) solution consisting of hybrid, silicon and III-V photovoltaic cells and a concentrator capable of collecting both diffuse and direct light within the same system.

Concentrating photovoltaics (CPV) provides the most efficient power generation for bright sunlight conditions. However, even in bright conditions, light contains a ‘direct’ and a ‘diffuse’ component, and on cloudy days, all of the light is diffuse. The direct component has a narrow range of incident angles coming directly from the sun itself, whereas the diffuse component, which arises from atmospheric scatter and reflections, has a broad range of incident angles. Concentrating photovoltaic optics are only able to focus a narrow range of angles onto the cells. The angular acceptance is dependent on the optical system, and in particular, the concentration ratio, but also the specific design. Angular acceptance ratios range from a fraction of one degree for typical CPV systems to a few degrees for micro-optical concentrating systems [1]. Because of this narrow acceptance angle, most of the diffuse light is lost and not converted to electrical energy.

In this project, we make use of a unique, micro-scale architecture [2] to create a novel hybrid CPV system. Micro-scale (sub-millimeter wide), multi-junction cells are attached to a large-area silicon cell backplane (several inches wide) that can optimally collect both direct and diffuse light, as shown in Figure 1. The use of micro-scale cells versus macro-scale cells has several advantages, including improved cell performance, better thermal management, new module form-factors, improved robustness to partial shading, and many others [3]. Micro-concentrating lenses collect the direct light and focus it on the micro-scale cells. Diffuse light is not focused (for the most part) and lands on the large-area silicon cell backplane as shown in the figure. By using multi-junction III-V cells (with or without the silicon backplane as a concentrated cell component), we can get the highest possible efficiency of the direct light input. In addition, by collecting the diffuse light in the large-area silicon cell, we can produce power on cloudy days when the concentrating cells would have minimal output. Through the use of micro-scale cells and lenses, the overall assembly will provide higher efficiency than conventional concentrators and flat plates, while keeping the form factor of a flat plate module.

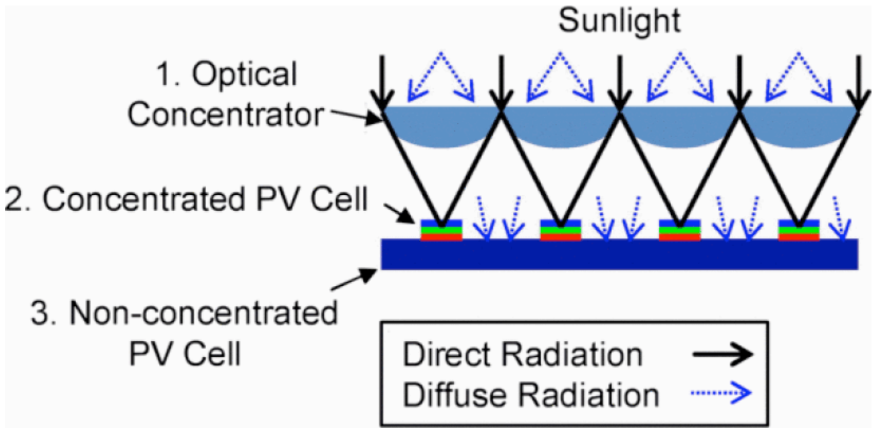


Figure 1 Schematic diagram of the hybrid CPV concept. Element (1) is an array of concentrating optical lenses. Element (2) is an array of III-V PV cell stacks, each about 1 mm wide, for concentrated light. Element (3) is a single large-area silicon PV cell, several inches wide. Concentrated light is collected by the III-V PV cell stack and the underlying silicon. Diffuse light is collected by the part of the silicon cell that is not covered by the III-V cells.

Prior Work and Direction

This project leveraged the capabilities and technology already developed at Sandia and the University of Delaware under an internally funded (Laboratory Directed Research and Development, LDRD) project, titled "Science-Enabled Next Generation Photovoltaics for Disruptive Advances in Solar Power and Global Energy Safety and Security," FY2012-14. This project was part of a multi-year, multi-million dollar series of projects that started around 2009. The effort is colloquially known as MEPV for Microsystems Enabled Photovoltaics. In this report we will refer to this internal effort as MEPV.

MEPV was focused on exploiting beneficial scaling effects in solar cells, modules, and systems to make solar power the lowest cost source of power available. The project explored new multi-junction, micro-scale solar cell architectures, new micro-optical concentration methods, and new hybrid solar collection concepts. It developed a series of prototypes to demonstrate these technologies. In addition, a detailed cost analysis was conducted to determine the costs of the proposed technologies and provide guidance for the system design efforts.

As originally conceived, depicted in Figure 2, approximately three to six 100 μm diameter, PV cells optimized for different wavelengths would be fabricated independently, then bonded together to form a stack. Each type of cell would be electrically connected independent of the other types of cells. A stack of cells would be placed on a carrier or handle wafer and under a micro-scale concentrating lens. The lens would be roughly 2 mm in diameter and provide 100 to 200 times optical concentration. The lenses and cell stacks would be arrayed on a pitch approximately equal to the diameter of the lens. The resulting module would only be a few millimeters thick. The predicted efficiency from such cell stacks is near 50%.

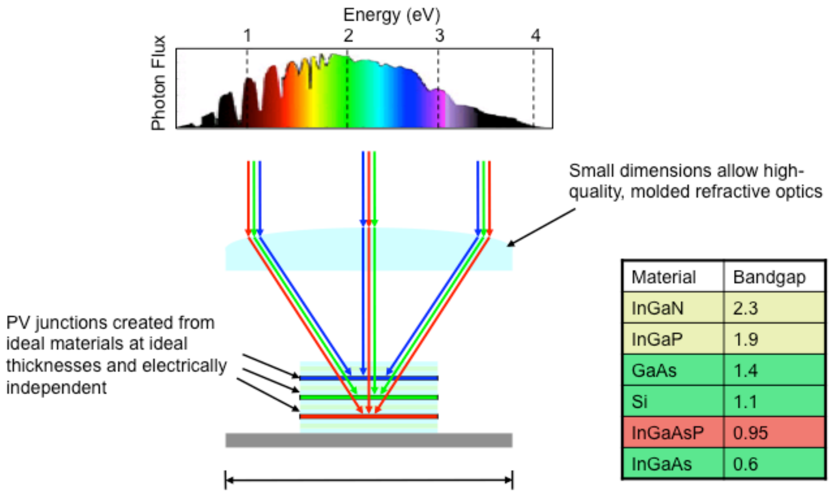


Figure 2 Conceptual MEPV multi-junction cell stack.

Advantages of this approach include:

- We can select ideal materials with respect to bandgap and efficiency without lattice matching or compatibility constraints (i.e. temperature processing, contamination, etc.).
- Individual contacts to each junction remove current matching, spectrum matching, and internal resistance challenges.
- Small dimensions allow high quality, molded refractive optics.

Some key features of the MEPV R&D effort include:

- The most efficient stack of micro-scale cells was sought, including a micro-scale silicon cell.
- The most efficient use of material was sought. This led to cells as small as possible, which is on the order of a few hundreds of microns in diameter, limited by the ability to form electrical contacts to the cells.
- To keep the manufacturing process parallel for as long as possible, the cell stack would be formed by wafer-to-wafer bonding. The cell stacks would be singulated after bonding. Then each stack would be placed on a handle wafer.
- For efficiency, the optical concentration should be on the order of 100 to 1000 times, leading to a lens diameter around 2 mm and a focal length around 5 mm.
- At this scale, simple spherical lenses (as opposed to the Fresnel lenses usually found in traditional CPV systems) can be molded in plastic without significant weight penalty.

- Using a compound lens system, the sun can be tracked up to ~10° by sliding the top lenses horizontally relative to the bottom lenses. This allows very coarse sun tracking with a cheap tracker and fine tracking within the panel, useful for windy conditions.

Some of the features of this approach served to increase the risk of this project because simultaneous technical advances were required in PV cell design, fabrication, and bonding. Later, we will discuss the difficulties we encountered.

ONR funding to demonstrate the hybrid CPV concept supplemented the LDRD investments and added scope to the work. In particular, prototype modules would be constructed for independent evaluation by the University of Delaware. The amount of funding was not sufficient to start with a completely fresh approach and this project depended upon the LDRD investment to achieve its goals.

Proposed Hybrid CPV Concept

The hybrid CPV concept emerged as the MEPV work progressed. It was realized that the handle wafer itself could be a silicon PV cell. So rather than incorporating a micro-scale silicon cell into the PV cell stack, a large-area conventional silicon cell was proposed as the substrate for the micro-concentrated PV cells, as depicted in Figure 1.

An example of the benefit of the hybrid architecture at various locations across the country is shown in Figure 3. The total efficiencies for collecting the direct and diffuse light are assumed to be 30% and 18% respectively, including the respective loss in the optical systems. The plot makes use of the annual direct and diffuse yearly solar radiation at various locations throughout the country. The plot shows that there is a substantial gain in generated power, independent of location. Of course, the percentage gain over the course of a year is greater in cloudy locations compared to sunny ones. Most importantly, the hybrid CPV system avoids an output that is nearly zero on cloudy days, but yields a substantial power output advantage over flat plate solar on sunny ones.

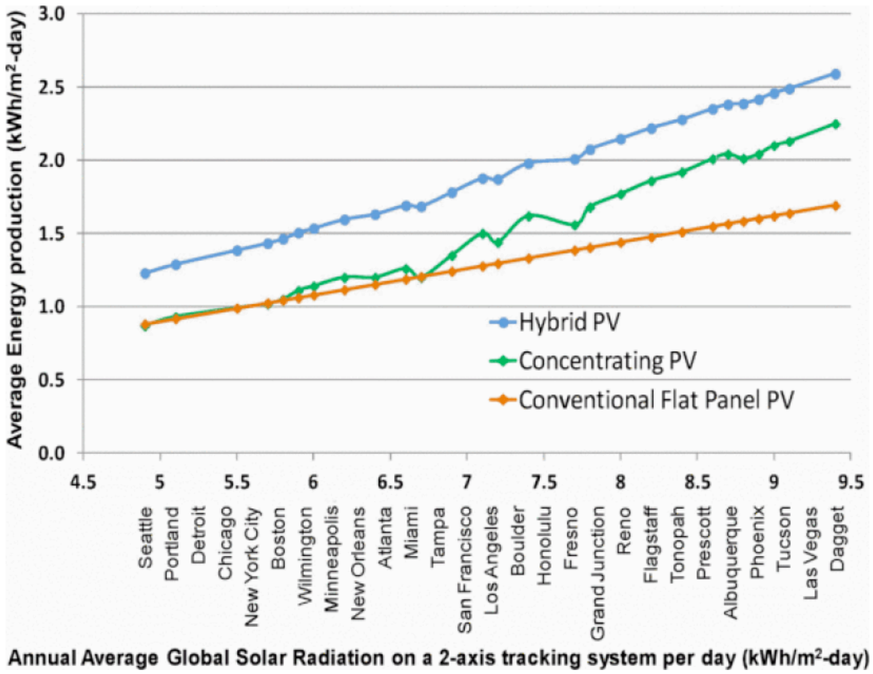


Figure 3 Energy production as a function of location comparing flat plate silicon PV, III-V Concentrating PV, and the hybrid CPV system.

This approach to solar power is only conceptual at this point. This project created a prototype hybrid CPV module to experimentally demonstrate the improvement in performance predicted by our calculations.
The technical challenges expected at the start of the project were minimal because the MEPV projects had already demonstrated:

- Fabrication of high efficiency silicon PV cells
- Bonding of III-V PV cells to silicon
- Electrical interconnection of cells
- Optical design and fabrication by molding of optical lenses
- Teamwork necessary to build prototypes

We expected incremental technical challenges including the design of the optics and the fabrication and alignment of more complex lenses. However, as will be explained in this report, both the MEPV program and this project encountered unexpected challenges and were unable to accomplish their final goals.

Nevertheless, we believe this project has demonstrated the concepts key to justifying further development.

Report Outline

The overall goal of this project was to experimentally demonstrate the hybrid CPV concept. Specifically, the project statement of work was:

- Fabricate the PV cell structure comprised of a large area, one-sun crystalline silicon PV cell, and the InGaP/GaAs dual junction concentrator cells.
- Assemble the micro-lens arrays, the fabricated PV cells, and the other module components to create a robust mini-module for demonstrating the hybrid module performance.
- Test the module prototype in a laboratory to characterize the performance under controlled conditions. Conduct follow-on outdoor testing in Albuquerque, NM, Newark, DE, and other locations as needed to evaluate system performance across a variety of solar conditions
- Analyze the data resulting from the experimental tests and produce a final project report.

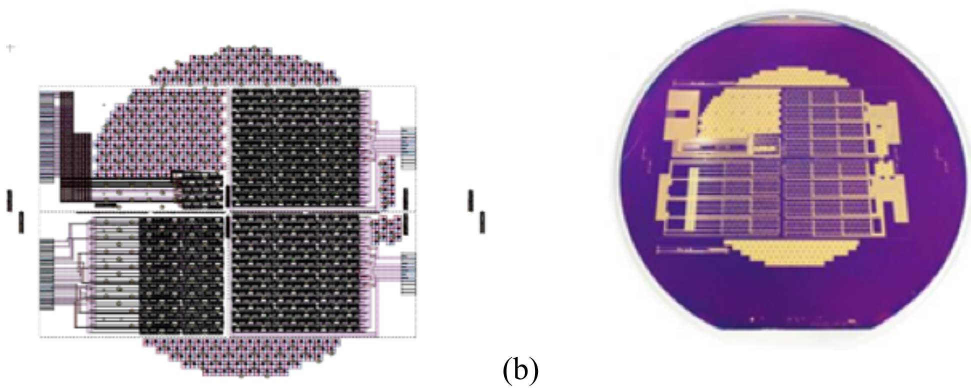
In Section 2 we discuss the design of the prototype, including the PV cells and optics. In Section 3 we present and discuss the experimental results. In Section 4 we present our conclusions and recommendations for future work to develop this concept into a practical system implementation.

2. PROTOTYPE DESIGN

The prototype is comprised of the following pieces: (1) A large-area, silicon PV cell that serves as the substrate or handle wafer and produces power from diffuse light. (2) Micro-scale compound semiconductor (III-V) PV cells that are bonded to the silicon handle wafer and produce power from concentrated sunlight. (3) Electrical connections between cells to form modules. (4) Micro-concentrating optical lenses that focus the sun on the micro-scale PV cells. These pieces are integrated into a prototype package and mounted onto a printed circuit board (PCB) for testing.

Design of the Silicon PV Cell

The silicon cell must be designed for two functions: to produce power from diffuse light and to be the substrate for mounting the micro-scale III-V cells. In its ultimate application, the silicon cell would be several inches square, e.g., 4” x 4” or 6” x 6”, similar to conventional cells. For the purposes of this prototype, a 6” wafer is divided to make four modules with different configurations, as shown in Figure 4.



(a) (b)

Figure 4 Silicon wafer before dicing into four prototype modules. (a) Contact lithography mask, (b) finished wafer showing silicon nitride film and metal.

To function as a large, single PV cell, we designed a front-contacted, inter-digitated PV cell. Diode junctions are made with alternating rows of p-doped and n-doped implants. All the p-doped areas are connected to one terminal by metal lines on the surface. All the n-doped areas are likewise connected to another terminal by metal lines. The metal connections cover roughly 20% of the surface. This cell collects diffuse light from 300 nm to 1100 nm. The prototype silicon cell is shown in Figure 5.

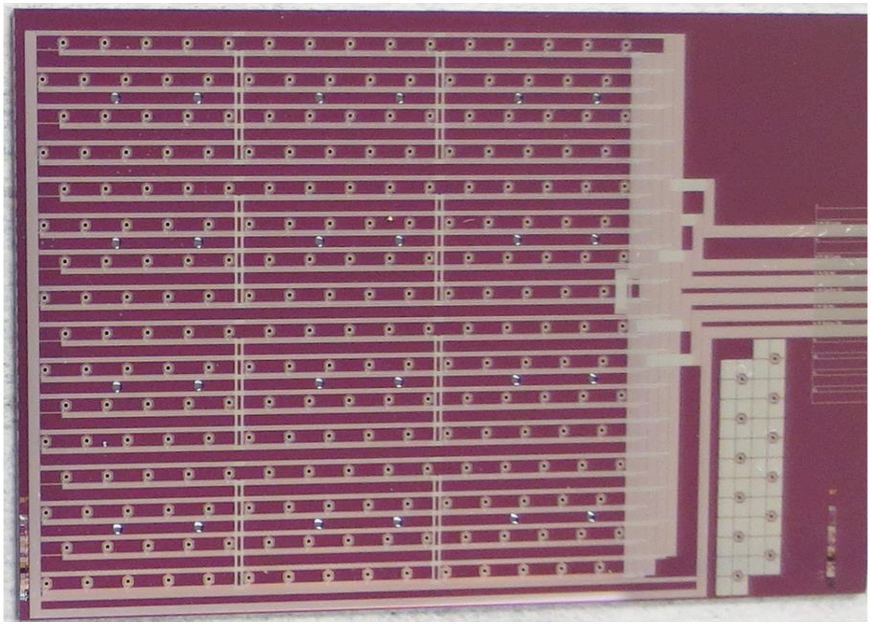


Figure 5 Prototype silicon cell showing alternating p- and n- contacting metal lines. The 240 cell mesas for bonding III-V cells are visible.

To function as the substrate for mounting the micro-scale III-V cells, flat cell mesas must be formed and covered with an optically thin, dielectric-bonding layer. These mesas are also seen in Figure 5.

Under the III-V cells, the silicon solar cell will collect the concentrated light remaining after passing through the III-V cell (870 to 1100 nm or roughly 1.1 eV to 1.4 eV). As illustrated in Figure 6, electrically separate contacts must be made to the silicon regions that collect concentrated light.

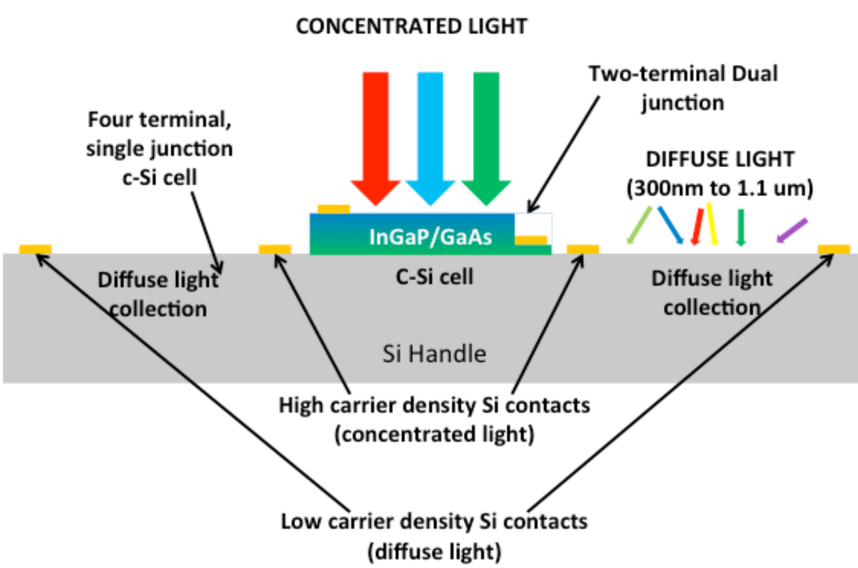


Figure 6 Cross section schematic of cells.

Design of III-V PV Cells

The micro-scale III-V cell is designed to be bonded to the silicon wafer using a wafer-to-wafer dielectric bonding process. The cell diameter is 250 µm on the open area window. Small size demands special design considerations for stacked cells, including a planar optical surface for bonding, no gridlines for the optical aperture, and careful attention to the sheet resistance of the contact layers. Typical cells structures have been altered to accommodate these needs. The cell contact layer thicknesses have been designed to minimize resistance. Contact layer materials are chosen to be transparent. Contact layers are designed to accommodate ohmic metal diffusion.

The prototype incorporates InGaP/GaAs dual junction series connected micro-scale cells. These cells absorb light with energy above 1.4 eV. The layer structure [4] is shown in Figure 7. A photograph of one cell is shown in Figure 8.

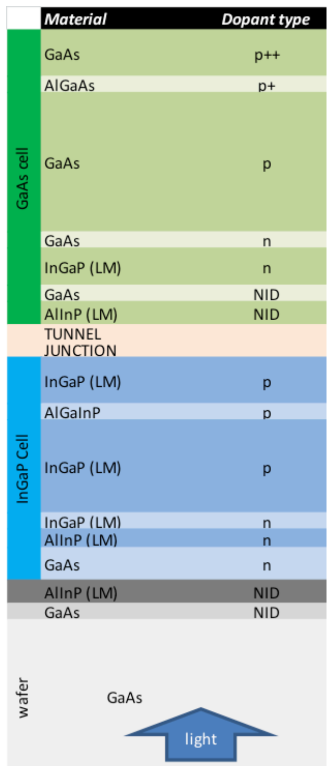


Figure 7 Semiconductor material layers for the InGAP/GaAs dual-junction cell.

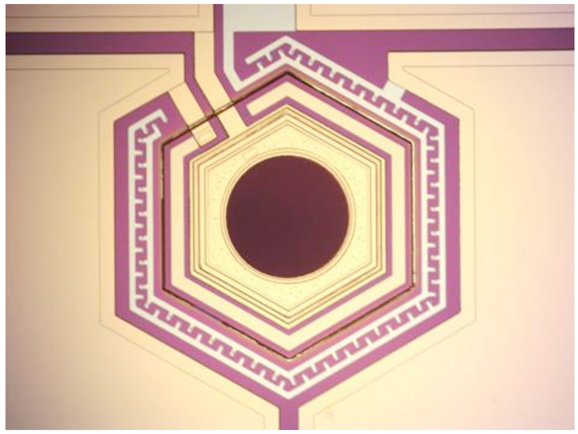


Figure 8 Photograph of an InGAP/GaAs cell bonded to silicon.

The cell is designed for wafer-to-wafer dielectric bonding to the silicon wafer. A special feature of this design is the incorporation of a sacrificial layer to release the micro-scale cells from the GaAs substrate wafer after bonding, depicted in Figure 9. The release process selectively dissolves the release layer using a common etch chemistry that does not attack metal or silicon nitride. The silicon mesa sidewalls are protected by silicon nitride. The release of bonded cells takes approximately 1.5 hours. Trenches etched around the InGaP/GaAs cells have been key to this process as deeper channels allow etchant to better access the liftoff layer. An etch stop layer deposited on the GaAs substrate prevents the etchant from reaching the substrate, so the substrate can be reused.

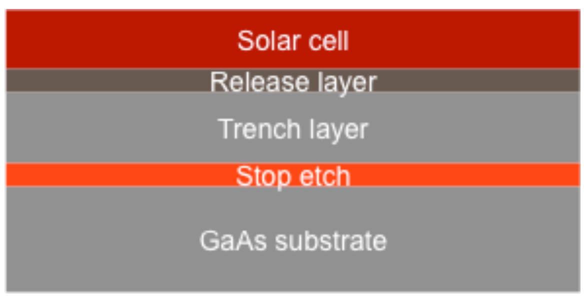


Figure 9 Cross-section schematic of material layers for III-V PV cell release.

The cells are bonded using dielectric bonding techniques [[5]]. Key features of the process include:

- Silicon cell mesas are formed prior to bonding. This allows the silicon cells to be processed before bonding.
- Bonding to the silicon wafer is a “backend” process with an alignment error of less than 10 μm.
- Optically thin (30 nm) PECVD silicon nitride (SiN) and thermal oxide are the bonding interface.
- The initial bond is a Van der Waals bond made on a contact aligner.
- Applying pressure and heat forms a stronger bond. A bladder bonder has given best results. Time and temperature need to be balanced to prevent cracking.

After bonding, the assembly cell can be treated like a standard silicon wafer, including high-temperature annealing of the contacts. Figure 10 shows a close-up of an InGaP/GaAs cell bonded to silicon. Figure 11 shows an infrared photograph of bonded wafers.

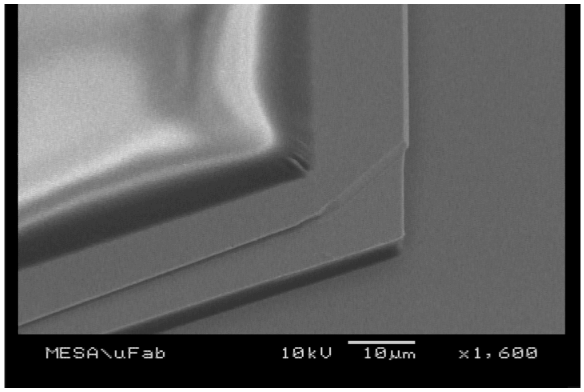


Figure 10 Close-up of an InGaP/GaAs cell bonded to silicon.

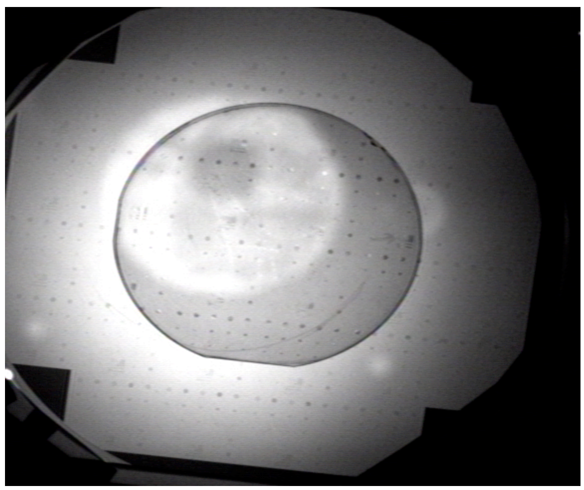


Figure 11 Infrared photograph of bonded wafers. The tiny specs are the III-V cells.

Hybrid Cell Integration

One of the many advantages of the MEPV approach is the ability to arbitrarily wire individual cells in series and parallel. This is illustrated in Figure 12 where a string of four cells is wired in series, three strings are wired in parallel, and these twelve cells form a unit that is used in further series and parallel combinations.

The prototype is designed to have 240 III-V cells. The cells were wired such that 5 were first connected in series and then 4 of those strings were connected in parallel. The expected output from this unit of 20 cells is around 10 V. This was repeated 12 times across the prototype to make 12 sub-modules, each measuring 35 by 42 mm, as shown in Figure 13.

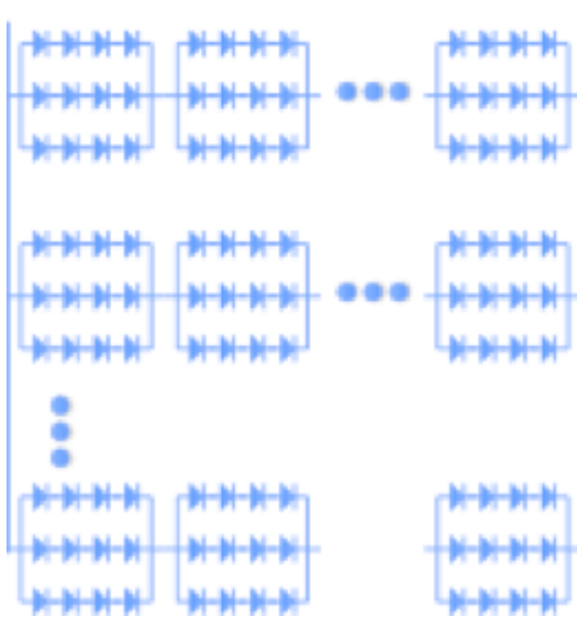


Figure 12 Conceptual electrical connection topology of PV cells in series and parallel.

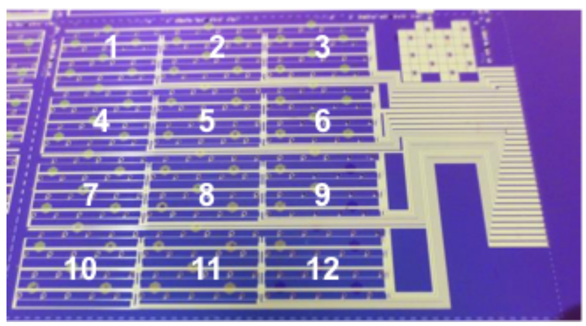


Figure 13 The prototype module is divided into 12 sub-modules.

Concentrating Optical Lenses

The design of the concentrating optics starts with the size of the III-V PV cells and the amount of concentration, which sets the diameter of the lenses. The greater the desired concentration is, the smaller the acceptance angle of the optics and the greater the required tracking accuracy. The lens material will determine the refractive index and transmission losses. Other important design considerations include chromatic aberration, cost, temperature stability, reliability, and durability.

Note that early MEPV optical designs were intended to incorporate fine sun tracking built into the module. The first MEPV prototype system had three compound lenses with the top two lenses fixed together and moving horizontally with respect to the third, bottom lens to allow approximately 10° of fine sun tracking. See Figure 14 and Figure 15. This allows the use of an inexpensive tracker for coarse sun tracking.

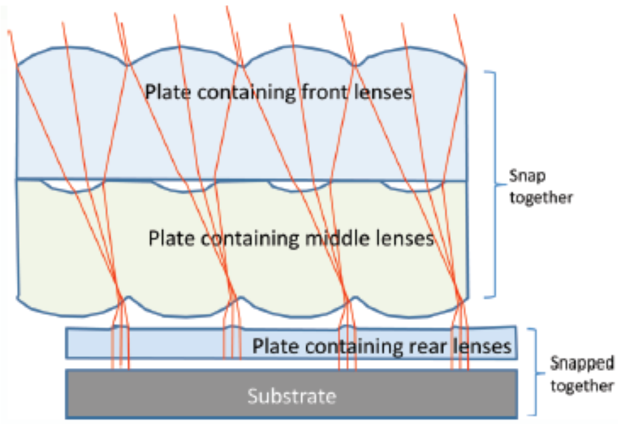


Figure 14 Cross-section schematic of optical lens arrays tracking the sun.

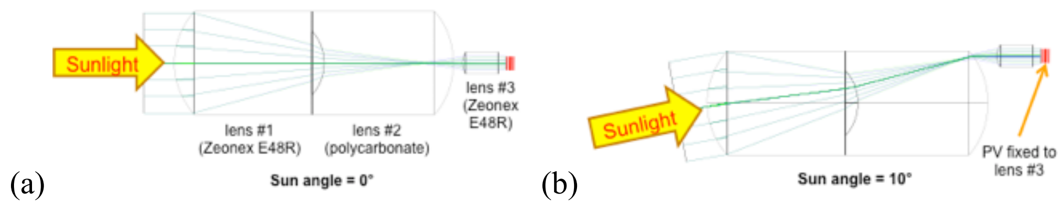


Figure 15 Optical ray tracing model with sun angle offset. (a) Offset 0°, (b) 10°.

As MEPV program progressed, it became apparent that fixing the two lens arrays and using a standard 2-axis tracker would be more cost effective. This approach would also be more reliable if the void between the lenses were to be filled with a solid so that moisture could not get in. Later, the LDRD project developed another design using only a single lens array that would be simpler and cost less.

The hybrid CPV prototype optical system is designed for 250μm-diameter solar cells, a 100X geometric concentration ratio, and a ±2.5° acceptance angle. As shown in Figure 16, each concentrator consists of two injection-molded polycarbonate lenses assembled together with a Sylgard® 184 PDMS filler layer between the optical plates. The lens materials will not pass light at energies above ~3eV (i.e., UV wavelengths shorter than ~400 nm). As shown in Figure 17, the unit cells are arranged in a 15x16 hexagonal array (close to 100% fill factor) with 2.381mm and 2.058mm pitch spacing respectively.

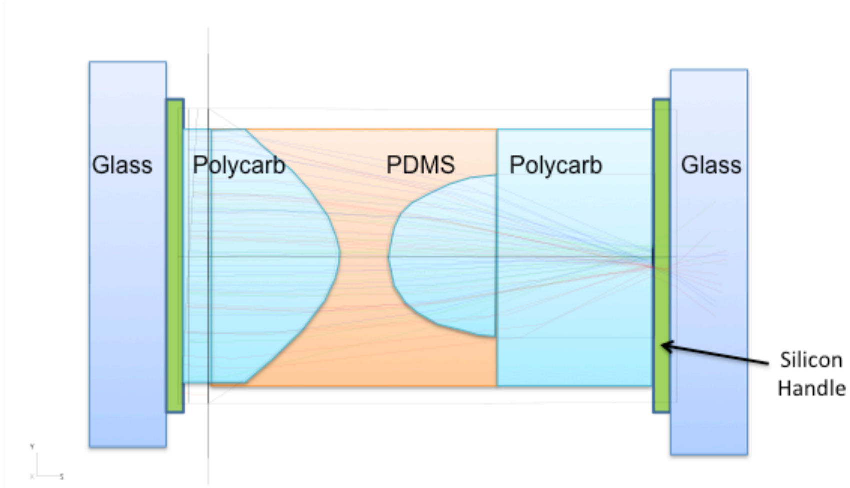


Figure 16 Illustration of the two lens optical concentrator.

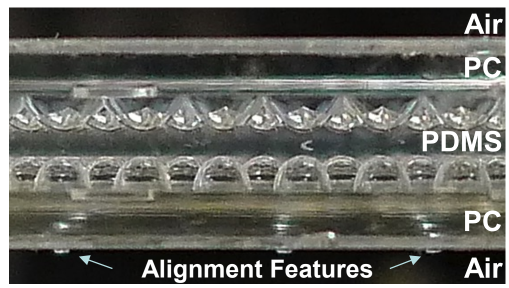
(a)  (b) 

Figure 17 Injection molded optical concentrator. (a) 15x16 lens array, (b) Cross-section.

3. RESULTS

In this section we describe the prototypes we made, experimental results, and discuss how the problems encountered might be resolved.

Prototype Fabrication

The project encountered problems with PV cell fabrication and integration that degraded the ability to produce the intended prototypes. First, the silicon cell performance was very poor. After a long investigation, we determined this to be caused by gold contamination in the MicroFab. This led us to make the prototype modules without active silicon cells. That is, only the III-V cells were electrically active.

Further, while the performance of individual III-V cells was very good as fabricated, the yield of functional cells in the assembly was very low due to problems with bonding and release. This led to randomness in functionality of the III-V cells integrated into the prototypes. That is, each sub-module had a random number and location of functioning cells. These problems and their future resolution are described in detail at the end of this section.

Three functional prototype units were made for this demonstration, in which the PV cells and optics were integrated and sandwiched between two pieces of glass, shown in Figure 18. The resulting module is less than 1.5 cm thick. The modules were then wire bonded and integrated into printed circuit boards so that they could be connected to field test setups, shown in Figure 19. The three units were designated Alpha, Beta and Gamma, shown in Figure 20.

The Alpha unit was put on long-term, outdoor durability test at Sandia's Photovoltaic Systems Evaluation Laboratory (PSEL). The Beta unit was tested at the individual cell level at Sandia in a solar simulator. Then the Beta unit was sent to the University of Delaware where the same cells were measured outdoors. They characterized the optical system and created a simulation model based on these measurements. The Gamma unit was tested at the sub-module level at Sandia in an indoor solar simulator and then again outdoors at the PSEL. A fourth, non-functional prototype was delivered to ONR.

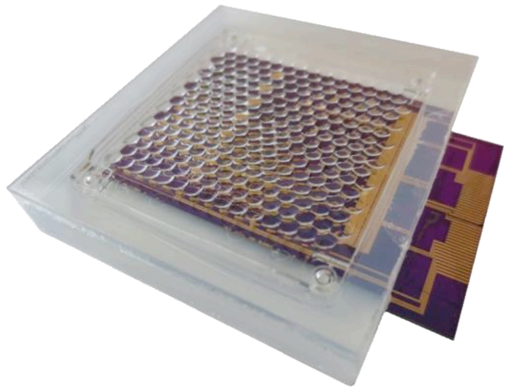


Figure 18 Photograph of an assembled hybrid CPV prototype module, sandwiched between glass.

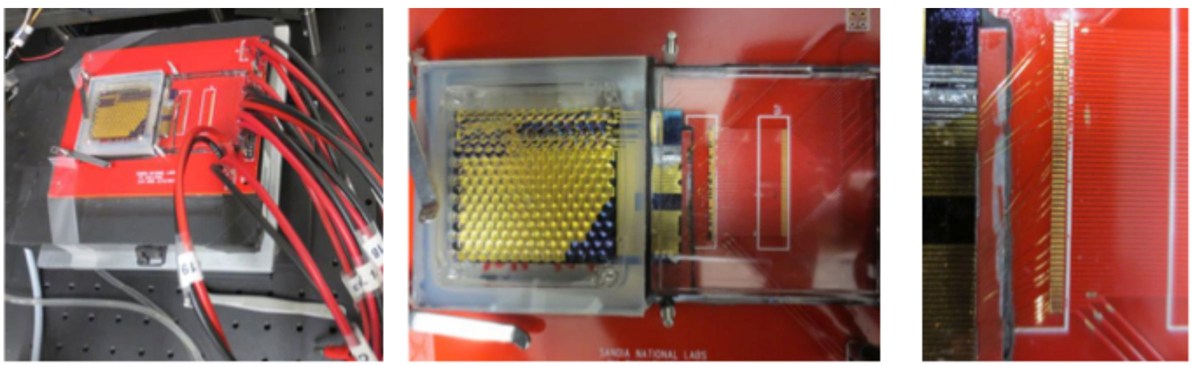


Figure 19 Packaged prototype mounted on a PCB showing close-ups of connections.

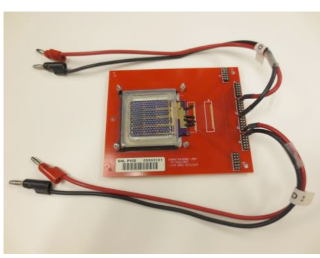
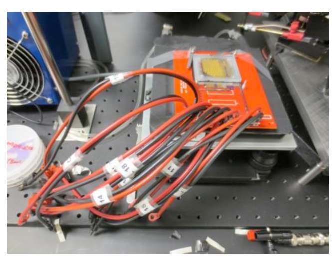
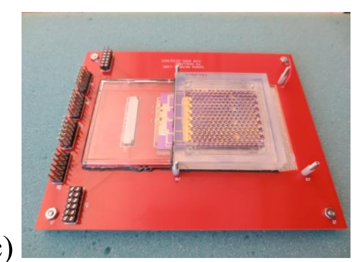
(a)  (b)  (c) 

Figure 20 Field test units. (a) Alpha, (b) Beta, (c) Gamma.

Experimental Results

Early Individual Cell Performance

Before making the prototypes, we achieved a one-sun efficiency of 23.6% for a combined III-V and silicon cell. As mentioned above, we discovered that the silicon cell performance was very poor, only 1-2%, which we determined to be due to gold contamination. Hence, the output of the combined III-V and silicon cell is almost entirely from the III-V cell. One-sun IV-curves for the silicon and III-V cell are shown in Figure 21.

On the other hand, the III-V, InGaP/GaAs cell efficiency was quite good relative to the best results in the literature. Figure 22 shows the characteristics of the cell under various concentration ratios. With 200X concentration, the cell efficiency improved to 29.5%.

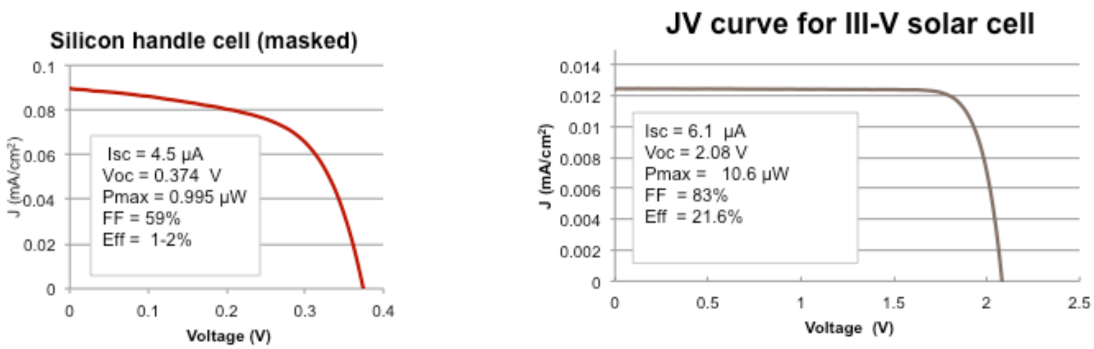


Figure 21 Cell IV measurements under 1-sun conditions for the silicon and III-V cell.

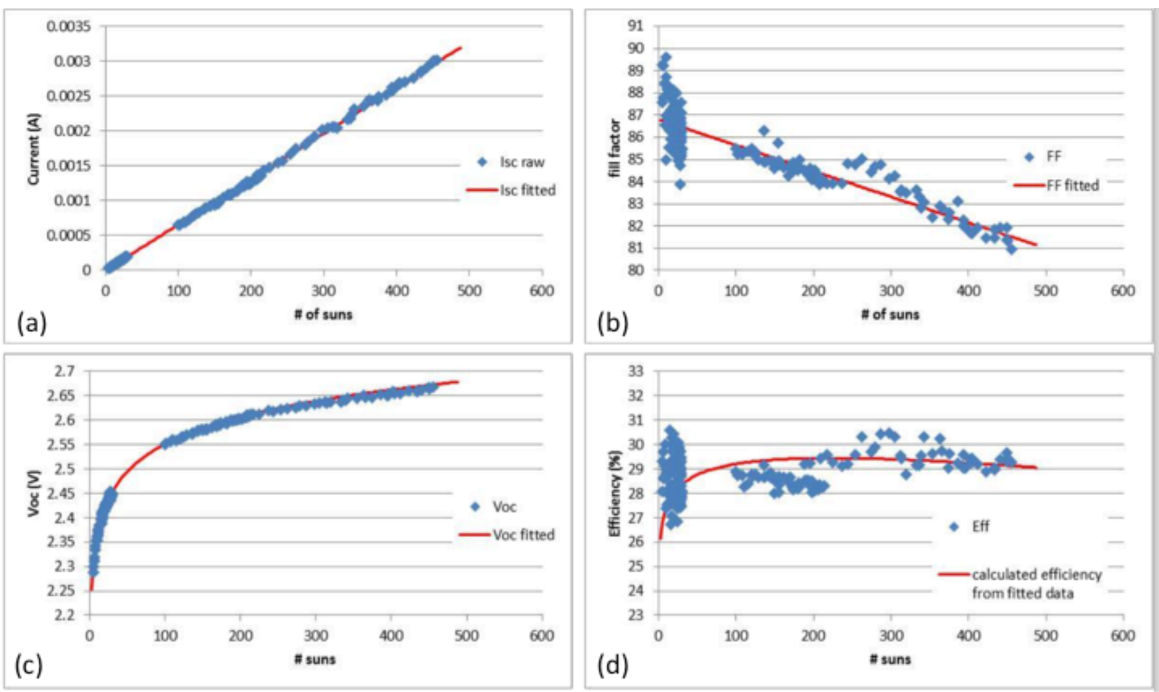
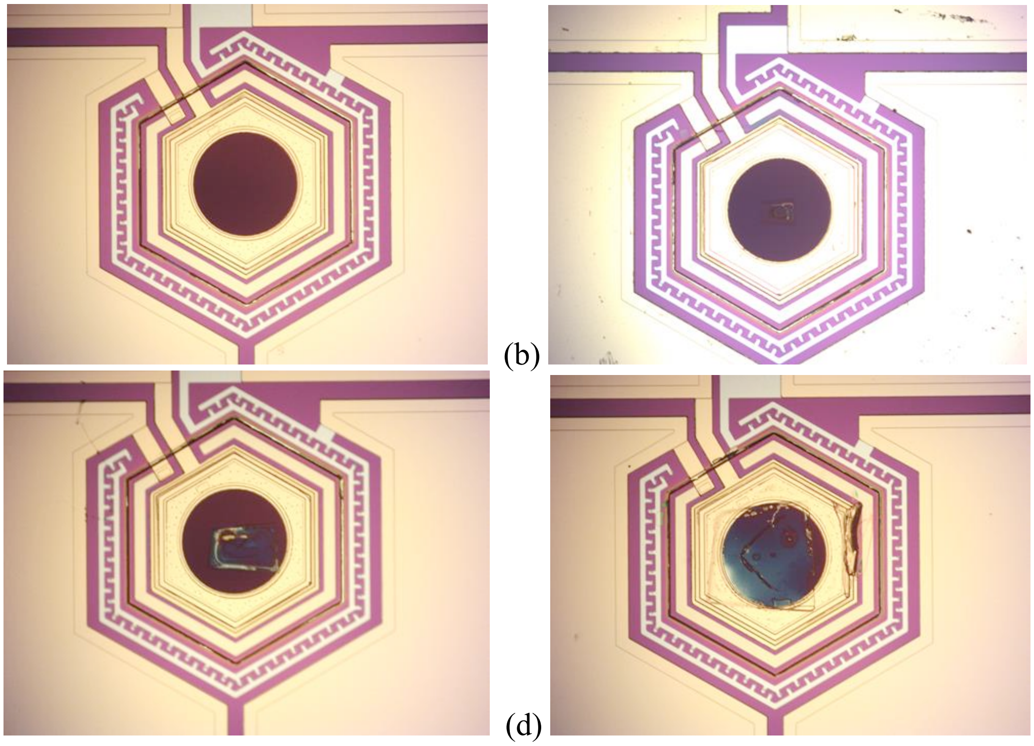


Figure 22 InGaP/GaAs cell performance under varying concentration ratios. (a) Current, (b) Fill factor, (c) Open circuit voltage (d) Efficiency.

We observed that III-V cell performance is directly related to the quality of the dielectric bond, cell release, and defects during processing. This is clearly shown in Figure 23 which shows photographs of four cells with efficiencies ranging from 20.5% down to 1%.



(a) (b) (c) (d)

Figure 23 Performance of III-V cells is related to quality of bond and release and defects during processing. Efficiencies: (a) 20.5%, (b) 18%, (c) 14%, (d) 1%.

Individual Cell Measurements on Prototype Beta

Recall that the Beta prototype unit was made without active silicon cells. That is, only the III-V cells were electrically active.

The cells were designed to be electrically connected into sub-modules. Some cells were left as individuals. The individual cells in the Beta unit were measured both at Sandia in the solar simulator and at University of Delaware outdoors. The results are shown in Figure 24. Sandia's indoor measurements ranged from 20.33% to 15.07%. The University of Delaware's outdoor measurements ranged from 20.26% to 9.43% for the same cells. The two measurements are reasonably close.

The cells with lower efficiency values had inadequate currents as opposed to poor fill factor, which consistently range between 83% and 85%. This indicates that there could be some window blockage, e.g., due to incomplete III-V substrate removal or particles generated in release covering the cell. Whereas, a recombination issue would more likely manifest itself as a lower open circuit voltage.

Cell	Pmax (uW)	Isc (uA)	Voc (V)	FF (%)	Eff. (%)
5	883.6	416.1	2.50	85.0%	18.00%
11	882.6	422.9	2.47	84.4%	17.98%
12	863.2	426.5	2.43	83.2%	17.58%
13	998.4	474.1	2.49	84.5%	20.33%
14	962.0	454.9	2.50	84.6%	19.59%
15	958.2	451.9	2.50	84.7%	19.52%
16	740.0	359.1	2.43	84.7%	15.07%
18	880.1	417.4	2.48	84.9%	17.93%
20	941.8	449.2	2.49	84.1%	19.18%

(a) Sandia Indoor Solar Simulator Measurements

Cell	Pmax (mW)	Isc (uA)	Voc (V)	Global (W/m2)	Direct (W/m2)	D/G%	FF (%)	Eff. (%)
5	747.4	365.0	2.40	1023	868	85%	85.3%	17.54%
11	550.0	276.0	2.35	1012	865	85%	84.8%	12.95%
12	595.4	313.0	2.31	1014	869	86%	82.3%	13.96%
13	860.0	418.0	2.41	1095	860	79%	85.4%	20.36%
14	791.9	386.0	2.41	966	833	86%	85.3%	19.36%
15	809.5	394.0	2.41	993	847	85%	85.4%	19.47%
16	393.4	202.2	2.31	976	850	87%	84.3%	9.43%
18	619.5	307.0	2.36	994	872	88%	85.5%	14.47%
20	803.9	398.0	2.38	1006	872	87%	84.8%	18.77%

(b) University of Delaware Outdoor Measurements

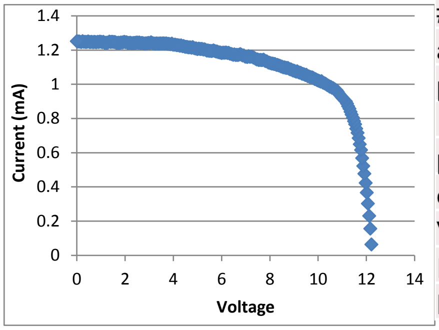
Figure 24 Measured efficiencies of single cells.

Indoor and Outdoor Sub-Module Measurements on Prototype Gamma

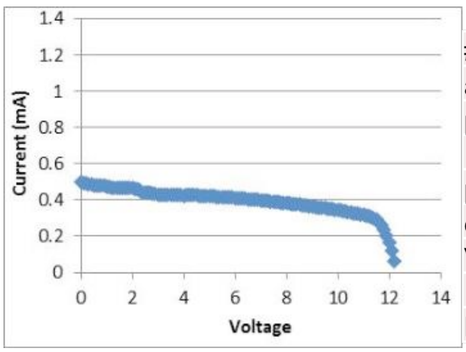
Recall that the Gamma prototype unit was made without active silicon cells. That is, only the III-V cells were electrically active.

Complete III-V sub-modules were comprised of 4 parallel strings of 5 series connected cells. However, we did not have any sub-modules with all cells working due to the problems mentioned above. In fact, because the cells are connected in series, a single non-functional cell in a string will cause the entire string to be non-functional. So we were able to measure the output from only four of the Beta unit's sub-modules. One module had 15 functioning cells, 3 strings of 5 cells, and the other three had 5 functioning cells apiece, 1 string of 5 cells.

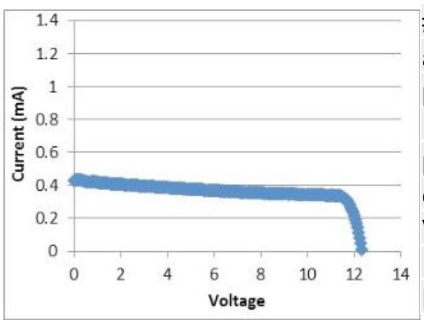
Figure 25 shows a summary of measurements from the indoor solar simulator. As expected, we get about three times the output power from the module with three strings of cells than from the single strings. The 15-cell sub-module had an efficiency of about 14%. The 5-cell sub-module efficiencies ranged from 11.5% – 16%.



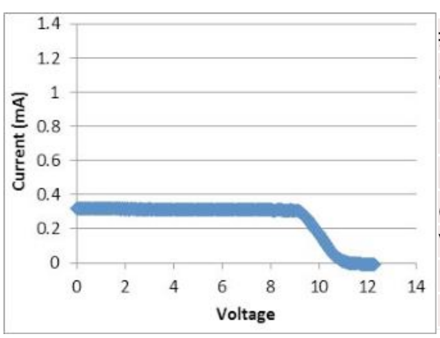
# cells	15	
area	0.735	cm^2
power	0.010374	W
	10.37399	mW
power density	14.11428	mW/cm2
efficiency	14.11428	%
Voc	12.212	V
Isc	1.2512	mA
FF	68%	



# cells	5	
area	0.245	cm^2
power	0.003554	W
	3.553632	mW
power density	14.50462	mW/cm2
efficiency	14.50462	%
Voc	12.4	V
Isc	0.50336	mA
FF	57%	



# cells	5	
area	0.245	cm^2
power	0.003915	W
	3.914995	mW
power density	15.97957	mW/cm2
efficiency	15.97957	%
Voc	12.356	V
Isc	0.43746	mA
FF	72%	



# cells	5	
area	0.245	cm^2
power	0.002835	W
	2.834962	mW
power density	11.57127	mW/cm2
efficiency	11.57127	%
Voc	12.308	V
Isc	0.32488	mA
FF	71%	

Figure 25 Sub-module measurement data from the Sandia solar simulator.

We expect the variability of individual cells to have the greatest effect on the output of a series connected string. The overall series connected output will be limited by the smallest output current. For strings in parallel, as in the 15-cell case, voltage mismatch also has an impact [6]. But, in general, the cells aren't as sensitive to voltage mismatch as to current mismatch. If we had higher yield and complete modules, we would expect that the series/parallel connections would have helped uphold the efficiency better than series only connected cells [7].

The Gamma prototype unit was then tested outdoors at the Sandia Photovoltaic Systems Evaluation Laboratory (PSEL). Figure 26 shows the mounting of the prototype on a high-precision sun tracker. Results from the outdoor test were similar to laboratory tests. Figure 27 shows a sample IV-curve for the 15-cell module. Figure 28 shows the results of measurements made under different lighting and temperature conditions.

Figure 26 Photographs of outdoor testing of the Gamma unit at Sandia PSEL.

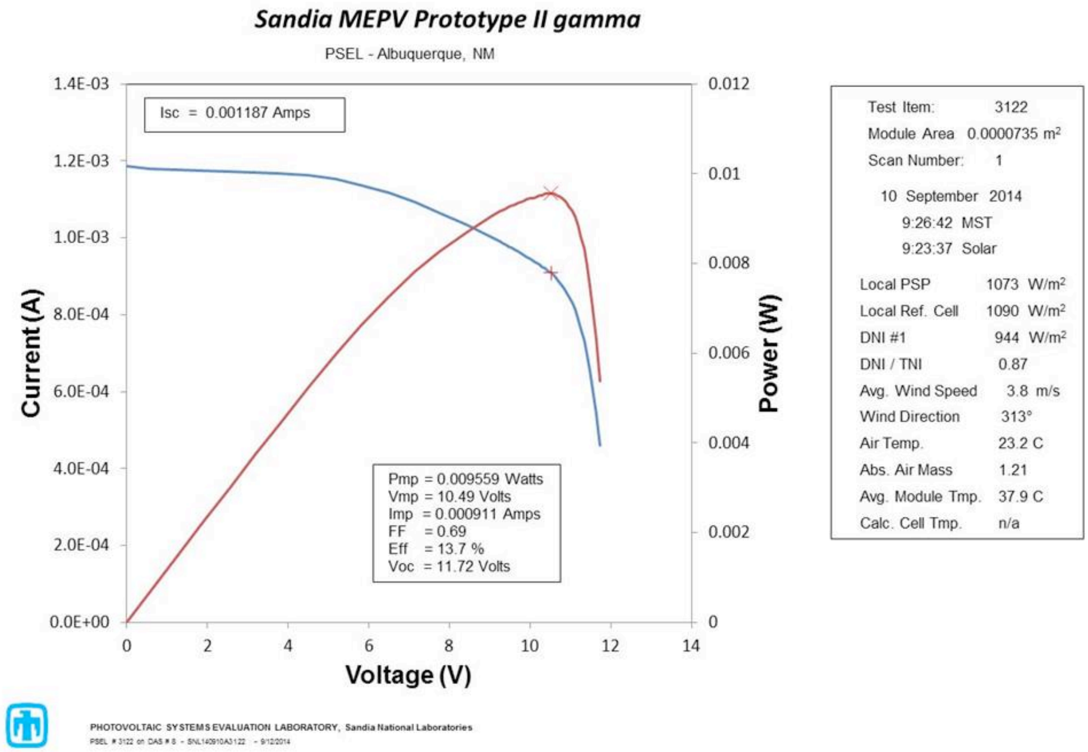


Figure 27 Example IV-curve from 15-cell sub-module at Sandia PSEL.

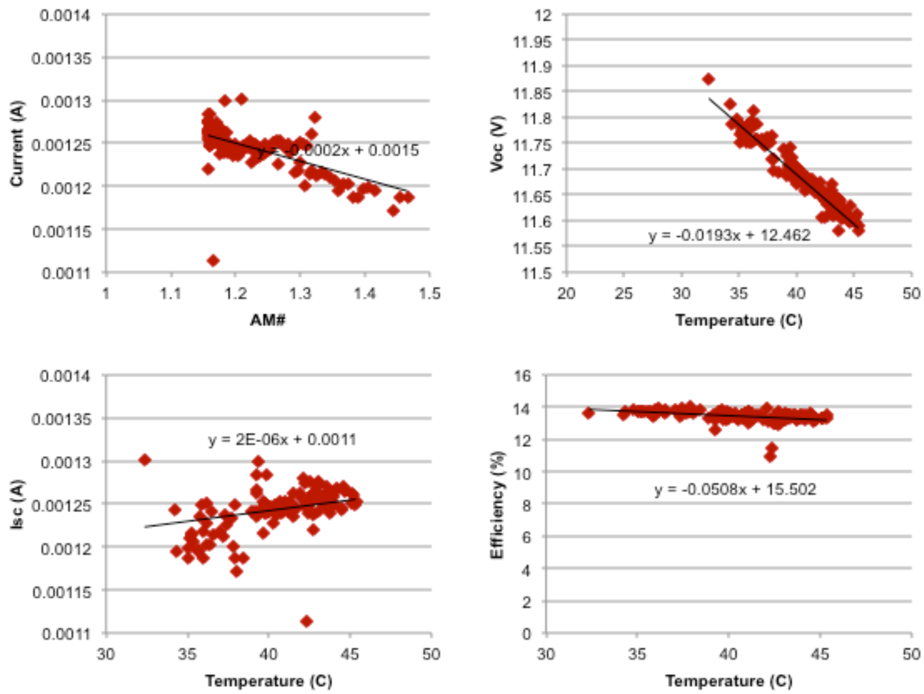


Figure 28 Outdoor measurements from 15-cell sub-module at PSEL made under different lighting and temperature conditions.

Measurements of Optical Performance on Prototype Beta

The University of Delaware characterized the optical system of the Beta unit. Measurements include: bulk transmission, concentrated spot size, outdoor concentrated transmission, and acceptance angle.

Bulk transmission: Spectroscopy measurements of the optical module using a Perkin Elmer Lambda 650 UV-Vis-IR spectrophotometer shows an AM1.5G weighted bulk transmission of ~87% over 400nm–1127nm (an air-module-air measurement without AR coatings), as illustrated in Figure 29.

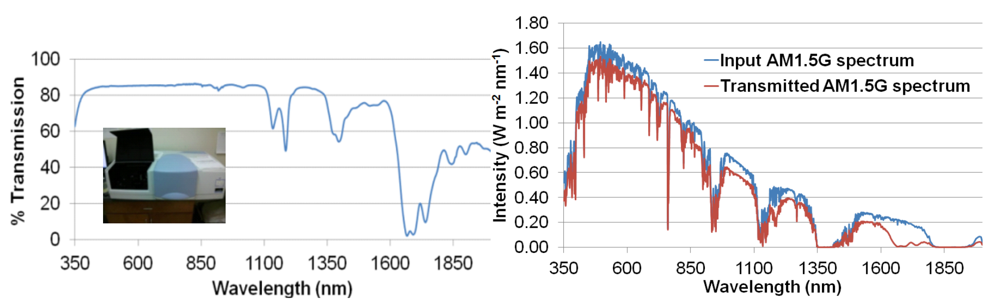


Figure 29 Bulk transmission spectroscopy. (a) Measured transmission, (b) AM1.5G weighted transmission.

Concentrated spot size: Using a halogen lamp white light source that simulates the solar disk's angular extent, a spot array at the output plane of the concentrator module is generated and captured by a camera, shown in Figure 30. The spot diagram shows an averaged focus spot size of ~50μm (FWHM).

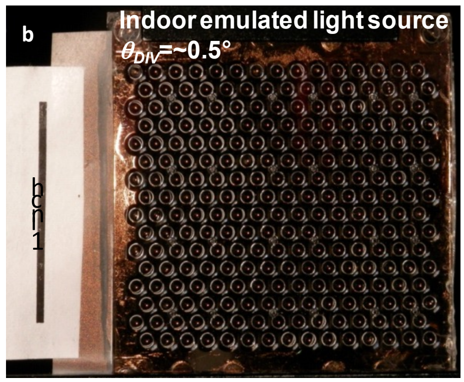


Figure 30 Spot array generated at the output plane.

Outdoor concentrated transmission: Concentrated transmission of the optical module was measured outdoor with the optical module mounted on a high-precision solar tracker. In order to the capture the concentrated sunlight that falls onto the designated cell region only, blocking masks with windows simulating the 250μm-diameter cells are assembled onto the optical module's rear surface via a PDMS layer. Figure 31 shows the measured outdoor concentrated transmission (air-module-air transmission) onto the cell region under various radiation conditions. The concentrated transmission under direct radiation is ~86.7%.

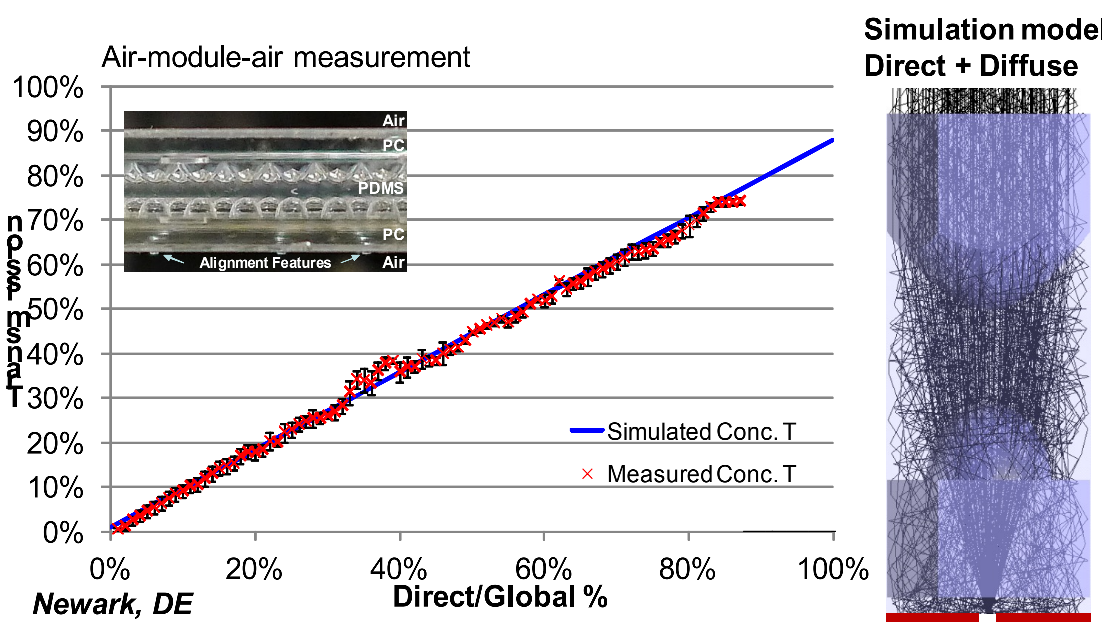


Figure 31 On-sun concentrated transmission measurements and optical simulation with AM 1.5 direct and diffuse sources.

Acceptance Angle: The acceptance angle of the optical module is measured outdoors using a fully packaged module with PV cells integrated with the micro-concentrator array. As shown in Figure 32, the optics achieve an on-sun acceptance angle of ~4.5° at full-width at 90% of peak and ~6.3° at full-width at half-maximum (FWHM). This provides sufficient angular tolerance for most low cost trackers, which have ~1°–1.5° tracking accuracy. Compared to the simulation model discussed next, the asymmetric shape of the experimental results is a possible indication of slight lateral misalignments between the front and rear optical components.

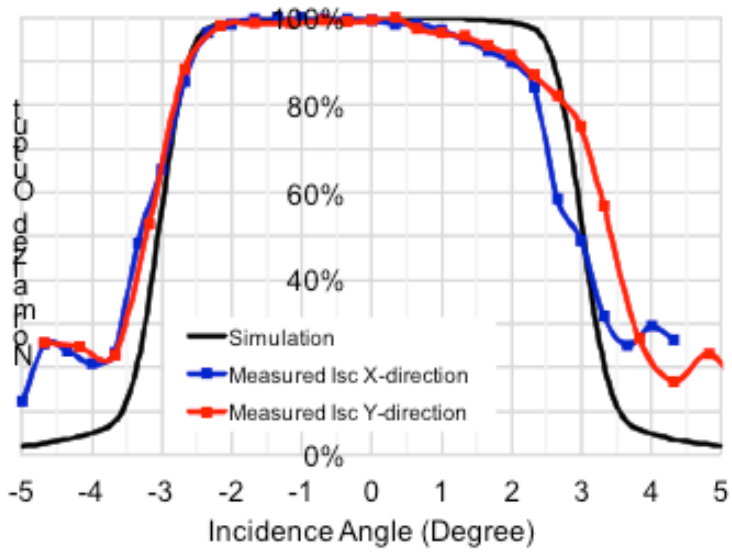


Figure 32 Concentrated optics acceptance angle.

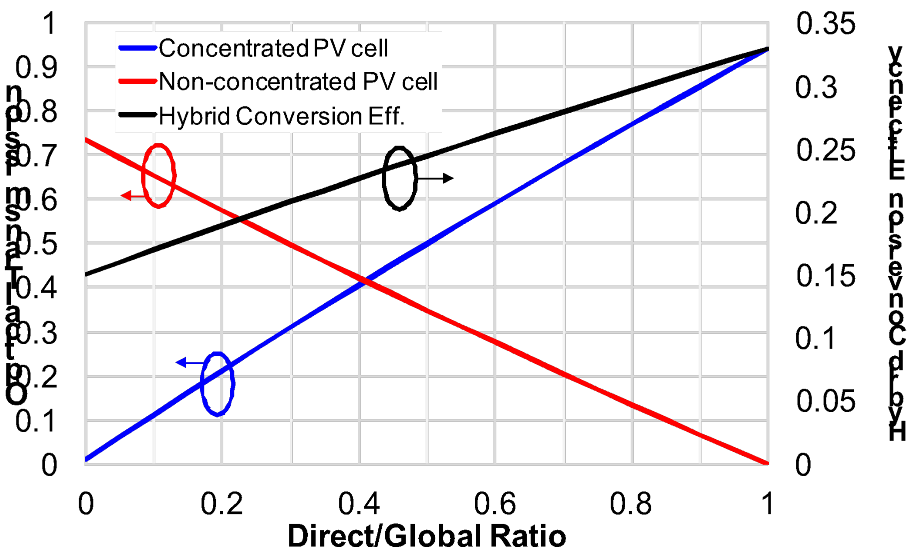
Optical Simulation Model

A 3D optical simulation model was constructed, incorporating measured data from the Beta unit, e.g., refractive indices, absorption, molded lens profiles, component thicknesses and distortions, etc..

Ray-trace simulations show that the air-module-air bulk transmission of the tested module is ~88%, under direct radiation with most of the optical power confined within the 250µm cell region. This is in good agreement with the measurements. Figures 31 and 32 compare the simulation results with measured data for outdoor concentrated transmission and acceptance angle, respectively. They also show good agreement.

With appropriate AR coatings and solar cells immersed in the secondary optic via an index matching layer, these simulations predict that the optical transmission of such micro-concentrator modules can achieve 93%. This indicates the potential of the current injection molding and assembly approach to realize high efficiency, low cost, and robust micro-optical concentrator modules.

Figure 33 shows the predicted performance under varying light conditions of a full hybrid CPV system assuming a 20% efficient silicon cell for diffuse light and 30% efficient III-V cells for concentrated light. Calculations indicate that in comparison to conventional flat plate silicon and concentrated PV, energy production could be increased by 40% (versus both) in cities with weather patterns like Seattle, WA, and by 43% and 18%, respectively, in cities like Las Vegas, NV.



$\eta_{Conc.\,cell}$ = 35%, $\eta_{Si\,cell}$ =20%.

Figure 33 Predictions from the optical simulation model. Note: left scale is Optical Transmission and right scale is Hybrid Conversion Efficiency.

Discussion

While we encountered problems with PV cell fabrication and integration that degraded our ability to produce the intended prototypes, we were able to demonstrate key elements of the hybrid CPV concept including:

- A large-area silicon cell designed to accept bonded III-V cells. However, gold contamination decreased silicon efficiency to 1-2%
- High-efficiency, micro-scale, dual-junction, III-V (InGaP/GaAs) cells designed to be bonded to the large-area silicon cell, >20% under one-sun and 29% at 200x concentration
- Combined silicon and III-V efficiency of 23% under one-sun, with the output almost entirely from the III-V cell
- Outdoor performance of 20% under real operating conditions for single III-V cells and up to 16% of III-V sub-modules (5 cells in series)
- Bonding of a GaAs wafer to the silicon cell wafer and then releasing the III-V cells from the GaAs substrate
- Series-parallel electrical connection of III-V cells
- Refractive optical lens with 100X concentration fabricated by injection molding
- Measured optical transmission of ~87%%, with projected transmission of 93%

An optical simulation model based upon measured data confirms the hybrid approach has distinct advantages over conventional PV, especially under diffuse light conditions

However we were unable to demonstrate the full functionality of a prototype module, because of problems with silicon cell fabrication and III-V cell integration. We discuss these problems and the path to their resolution below.

Silicon PV Cell Fabrication

Sandia has two semiconductor fabrication facilities, the SiFab and the MicroFab. The SiFab is a CMOS production facility and enforces strict discipline over what materials are allowed in the fab to prevent contamination. The MicroFab is a compound semiconductor research and production facility and allows a wider range of materials, because compound semiconductors are less sensitive to contamination. In the past we were able to achieve efficiencies higher than 15% in silicon cells [8] when all the processing was done in the SiFab.

As discussed, we designed the cells to be bonded with dielectric materials, i.e., silicon nitride and oxides. This approach maximizes efficiency by eliminating the need for antireflective coatings between cells, which would have been required with more standard flip-chip bonding processes. So in order to improve our ability to make good bonds, the original silicon cell process was changed to complete the latter steps of the silicon cell in the MicroFab, where the bonders are located. However, then efficiencies went down compared to cells fabricated wholly in the SiFab. After a long, detailed investigation, the low silicon cell efficiency was finally attributed to gold contamination.

We were concerned about heavy metals contamination when the process was transferred from the SiFab to the MicroFab. So we took precautions regarding which tools we would use. We first suspected heavy metal contamination when the efficiency of the silicon cell decreased rather than increased after annealing in an oven in the MicroFab. We confirmed contamination by sending several test wafers through the tools we used and making measurements at each step. We demonstrated a high content of gold in more tools than we expected, including the diffusion ovens, wet benches, and reactive ion-etch tools.

Moving silicon cell fabrication back to the SiFab can easily solve the gold contamination problem. An alternative approach would be to place a thick dielectric diffusion barrier on the silicon to prevent the migration of gold into the silicon.

Other reasons for low efficiency relate to the design of the silicon cell. (1) The design had a large distance between n- and p- type collectors to allow for a pristine bonding area. (2) The front-side metal covers about 20% of the surface, which blocks a significant amount of light. Both of these problems can be addressed in a new design, e.g., a front- and back-connected cell.

III-V Cell Integration and Yield

The yield of functioning integrated III-V cells was only about 20%. The low yield was due primarily to large stresses induced by the mismatch between the coefficients of thermal expansion (CTE) of silicon and the III-V materials and by the large bonding area. These stresses caused premature rupture and release of cells when the stack was submerged in the release agent. The rupture of the cells created cell fragments that floated to locations that led to electrical shorts or to decreased light absorption.

The low yield of III-V cells was also due to bonding issues. We observed that implanted silicon is not a good surface for bonding, as the implants roughen the surface. Cleanliness is also vital to a good bond. In later MEPV work, we changed the cell design by not implanting the silicon below the III-V cell-bonding region. This means the silicon does not participate in producing power under concentrated light. We also improved cleanliness by leaving the wafers in the SiFab until the day needed for bonding. The overall bonding yield after those measures were adopted was as high as 90% (with imperfections mostly due to edge defects on the wafer).

4. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The objective of this project was to demonstrate a novel hybrid CPV concept, enabled by micro-scale PV cells, focusing direct sunlight with concentrating lenses on III-V PV cells and collecting diffuse light with a large-area silicon cell, while keeping the form factor of a flat plate module. The hybrid approach offers the best of two approaches, a multi-junction cell for direct light and a flat panel cell for diffuse light. We have demonstrated key elements of the concept. While we were unable to demonstrate a full functioning prototype due to problems with silicon cell fabrication and III-V cell integration, we believe this project has demonstrated the concepts key to justifying further development.

We believe that the path to very efficient hybrid systems is known. Perhaps the hardest issue with the technology is scale-up. It proved hard enough for us to make 2" modules. Making even a single demonstration system of a few kW would require us to adopt medium-scale manufacturing techniques. The path from research prototype to manufacturing can be expensive for new technologies such as this. Yet we are confident that the hybrid approach has sufficiently strong advantages in efficiency compared to both flat-plate and concentrating systems that it would be worth the investment to bring the technology to fruition for a customer who wants maximum output.

Considerations for Future Work

As stated several times above, there were two areas where we fell short. First, we did not achieve good silicon cell efficiency, resulting in very little power from the silicon cell. Second, the yield on the fabrication of the III-V cells was low, resulting in low power from the module. Together, these caused us to be unable to demonstrate the ultimate goal of module efficiency. Below we consider how these problems can be fixed in future work.

To improve the efficiency of silicon PV:

There is no fundamental reason why we cannot achieve 20% efficient silicon cells. Conventional commercial multi-crystalline silicon cells under one sun, have module efficiencies between 17%-19% (Yingli) and single crystalline cells have demonstrate module efficiencies of up to 21% (Sunpower). Record silicon cells under concentration have achieved efficiencies up to 25%.

We suffered gold contamination in the MicroFab. We can solve this easily by either moving the process back to the SiFab. Or in the MicroFab, we could use tools dedicated to the processing of silicon and incorporate a thick dielectric diffusion barrier on the silicon to avoid contamination by heavy metals.

Regarding silicon cell design, the design can be changed to have front-to-back contacts or all back contacts, using a double polished silicon wafer. The metal coverage problem can be solved if we switch from wide and short wires made by metal evaporation to thin and tall wires made by electroplating. Other approaches might include using a transparent metal such as Indium Tin Oxide.

To improve the efficiency of III-V yield:

Similarly, single junction GaAs cells have achieved efficiencies up to 28.8% (Alta Devices), dual junction 31.1% (NREL), triple junction 37.9% (Sharp IMM) and 38.8% for a five junction (Spectrolab).

Simple flip-chip bonding, rather than dielectric bonding, can improve the assembled yield of the III-V cells. Similar flip-chip bonding and assembly processes are routinely used to make focal plane arrays at Sandia and elsewhere. High yields (>99.9%) are routinely achieved when bonding photodetectors to silicon read-out integrated circuits.

The downside of the flip-chip approach is that there is a gap between the III-V and silicon cells that needs to be index matched. If the gap is air, we simply need standard antireflection coatings on each cell at the interface. While slightly less efficient than dielectric bonding in optical transmission, the processing simplifications leading to higher efficiency silicon cells and higher bonding yields would have more than made up for the slight additional losses in the two coatings.

Also, slightly larger cells would facilitate handling by flip-chip robots.

Recommendations for Future Work

The proposed path forward is to redesign the module to be more tolerant of variation, easier to assemble, and so on. We suggest that future work:

- Do all silicon processing in the SiFab or add a dielectric diffusion barrier to prevent contamination in the MicroFab.
- Use standard high efficiency III-V cells with AR coatings.
- Use flip-chip technology to create aligned bonds.
- Use a simpler optical design with only one lens array.
- Use larger diameter cells to aid pick-and-place assembly and to make alignment of optical elements easier.

REFERENCES

[1] B. H. Jared, M. P. Saavedra, B. J. Anderson, R. S. Goeke, W. C. Sweatt, G. N. Nielson, M. Okandan, B. Elisberg, D. Snively, J. Duncan, T. Gu, G. Agrawal, and M. W. Haney, "Micro-concentrators for a microsystems-enabled photovoltaic system", *Optics Express* Vol. 22, Issue S2, pp. A521-A527 (2014) doi: 10.1364/OE.22.00A521

[2] M. W. Haney, T. Gu, and G. Agrawal, "Hybrid micro-scale CPV/PV architecture," in *Photovoltaic Specialist Conference (PVSC), 2014 IEEE 40th*, pp.2122-2126, 8-13 June 2014 doi: 10.1109/PVSC.2014.6925343

[3] G.N. Nielson, M. Okandan, J. L. Cruz-Campa, P. J. Resnick, M. W. Wanlass, P. J. Clews, T. C. Pluym, C. A. Sanchez, and V. P. Gupta, "Microfabrication of microsystem-enabled photovoltaic (MEPV) cells", in Advanced Fabrication Technologies for Micro/Nano Optics and Photonics IV, W. V. Schoenfeld, J. J. Wang, M. Loncar, T. J. Suleski, Editors, Proceedings of SPIE Vol. 7927 (SPIE, Bellingham, WA 2011), 79270P

[4] A. Tauke-Pedretti, et. al. "Integrating III-V Compound Semiconductors with Si for Advanced Multi-junction Solar Cells" Photonics West 2015

[5] A. Tauke-Pedretti, J. G. Cederberg, J. L. Cruz-Campa, C. Alford, C. A. Sanchez, I. Luna, J. S. Nelson, and G. N. Nielson, "Bonded InGaAs cells for microsystems enabled photovoltaics," in *Photovoltaic Specialist Conference (PVSC),* 2014 IEEE 40th, vol., no., pp.0546-0549, 8-13 June 2014 doi: 10.1109/PVSC.2014.6924979

[6] A. L. Lentine, G. N. Nielson, M. Okandan, J. L. Cruz-Campa, and A. Tauke-Pedretti, "Voltage Matching and Optimal Cell Compositions for Microsystem-Enabled Photovoltaic Modules," *in IEEE Journal of Photovoltaics*, vol.4, no.6, pp.1593-1602, Nov. 2014 doi: 10.1109/JPHOTOV.2014.2345437

[7] A. L. Lentine, G. N. Nielson, M. Okandan, W. C. Sweatt, J. L. Cruz-Campa, W. C. Sweatt, and V. Gupta, "Optimal cell connections for improved shading, reliability, and spectral performance of microsystem enabled photovoltaic (MEPV) modules," *in Photovoltaic Specialists Conference (PVSC),* 2010 35th IEEE , vol., no., pp.003048-003054, 20-25 June 2010

[8] J. L. Cruz-Campa, M. Okandan, P. J. Resnick, P. Clews, T. Pluym, R. H. Grubbs, V. P. Gupta, D. Zubia, and G. N. Nielson "Microsystems enabled photovoltaics: 14.9% efficient 14μm thick crystalline silicon solar cell," *Solar Energy Materials and Solar Cells* 02/2011; 95(2):551-558. DOI: 10.1016/j.solmat.2010.09.015

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