New US Ultra High Efficiency R&D Programme

Allen Barnett[1], Douglas Kirkpatrick[2], Christiana Honsberg[1]
[1]University of Delaware, Electrical and Computer Engineering, Newark, DE, USA 19716-3130
[2]Defense Advanced Research Projects Agency (DARPA), 3701 North Fairfax Drive
Arlington, VA 22203-1714

ABSTRACT

Very high efficiency is an important characteristic of the value proposition for solar to electric conversion. High efficiency is the shortest path to cost-effective commercial applications and leads to new high value applications such as portable battery charging. The Defense Advanced Research Projects Agency has initiated the Very High Efficiency Solar Cell (VHESC) program to address the critical need of the soldier for power in the field. Very High Efficiency Solar Cells for portable applications[1,2] that operate at greater than 55 percent efficiency in the laboratory and 50 percent in production are being developed. We are integrating the optical design with the solar cell design, and have entered previously unoccupied design space that leads to a new architecture paradigm. An integrated team effort is now underway that requires us to invent, develop and transfer to production these new solar cells. Our approach is driven by proven quantitative models for the solar cell design, the optical design and the integration of these designs. We start with a very high performance crystalline silicon solar cell platform. Examples will be presented. Initial solar cell device results are shown for devices fabricated in geometries designed for this VHESC Program.

Keywords: Solar cell, high-efficiency, architectures

1. INTRODUCTION

The realization of a high efficiency solar cell which is also manufacturable is the defining problem of photovoltaics. Our rigorous, model-driven approach overcomes limitations of existing approaches by developing an integrated optical and solar cell design which has efficiency greater than 55% at low concentration levels as well as multiple paths to low cost.

The potential for a technology breakthrough in creating 50% efficient solar cells became apparent to the Defense Advanced Research Projects Agency because of a series of recent developments in several – otherwise unrelated – technology areas including biotechnology, non-imaging optics, and novel solar cell architecture designs. The potential to synthesize and fabricate solar cell materials in new ways that eliminate some key constraints in materials geometry or selection, the ability to cost effectively split the solar spectrum into different energy bins at efficiencies approaching 95%, and the development of new solar cell architectures with the potential to highly leverage these new capabilities all pointed towards an opportunity for a true breakthrough in solar cell performance. In response, the Defense Advanced Research Projects Agency (DARPA) launched the Very High Efficiency Solar Cell (VHESC) program with the objective of developing and demonstrating 1,000 prototypes devices with 50% efficiency and a peak output of 0.5 W, cost effectively, all to be completed by the end of calendar year 2009.

A key aspect of the program is the mitigation of risk through a team approach and the use of multiple parallel paths in areas of high risk development. Almost as important is the ability of that team to integrate the diverse disciplines that are the source of the technologically enabling breakthroughs and integrate them into a single effort focused on high efficiency solar cell development. The technological areas providing the underpinning of the opportunity come from outside the existing solar cell development community, and providing the structure to focus these developments onto the solar cell problem is perhaps the biggest challenge of all.

Our central innovation is to co-design the optical, interconnect and solar cell design, which dramatically increases the design space for high performance photovoltaics in terms of materials, device structures and manufacturing technology. This approach allows multiple benefits, including increased theoretical efficiency, new architectures which circumvent existing material/cost trade-offs, improved performance from non-ideal materials, device designs that can more closely approach ideal performance limits for existing solar technology (including silicon solar cells), reduced spectral mismatch losses and increased flexibility in material choices. An integrated optical/solar cell allows efficiency improvements while retaining low areal costs, and hence expands the applications for photovoltaics. It allows a design approach which focuses first on performance, enabling the use of existing state-of-the-art photovoltaic technology to design high performance, low cost multiple junction III-Vs for the high and low energy photons and a new silicon solar cell for the mid-energy photons, all while circumventing existing cost drivers through novel solar cell architectures and optical elements.

2. MOTIVATION

Today's soldier on the battlefield is carrying loads of over a hundred pounds including his pack, weapon, protective gear, and the ever present suite of electrical gadgets that defines today's high tech warrior. Of that load, the average soldier carries 20 pounds of spare batteries to keep the technological edge that Night Vision Goggles, multifunction radios, laser rangefinders, and GPS mapping systems provide up and operating. But that high tech edge is a two-edged sword: every extra pound that the soldier is burdened with counts against their mobility and reaction times. Reducing or eliminating the spare-battery burden will dramatically improve the choices over those that today's soldier must make about what to take and what to leave behind.

The other side to the battery challenge is the logistical tail of keeping a combat force supplied with quantities they consume – that soldier's 20-pound battery load may only last three to seven days in active combat. The cost of keeping that supply chain filled is large – military airlift transport to airfields that may or may not be secure, followed by helicopter or ground transport to a re-supply staging area. The cost in people, materiel, and transport assets to keep this supply chain filled is staggering.

Eliminating the spare battery burden requires integrating an inexpensive renewable portable power supply into the soldiers existing suite of battery-hungry tactical tools – starting with radios and proceeding on to flashlights, laptops, and other gear. The only worldwide readily available source of energy for this purpose is solar power – but current solar cell technologies are too large and heavy to present an attractive alternative to spare batteries. A state of the art tactical battlefield flashlight, for example, requires a 0.5W cell to provide approximately 45 minutes of flashlight operation per night, given an 8-hour recharge cycle during the day. That amount of on-time is on the high end of the usage curve, but not uncommon. Providing the 0.5W of cell power requires 33 cm^2 active area module if the efficiency were 15% - common performance for high quality Silicon cells today. There's only one big problem: there isn't 33 cm^2 available to add to solar cell to the flashlight – the maximum available area is more like 10 cm^2.

Flashlights are not unique in this regard. An inspection of the most commonly used battlefield electronic devices convolved with typical usage scenarios for those devices consistently drives a need for solar cells with 45-50% efficiencies if direct device integration is the target. Alternatives to direct device integration include a single recharging device and/or flexible solar cells that might be folded or rolled up into a compact size for carrying. Unfortunately neither of these approaches covers the spectrum of needs for a soldier in the field. A single recharging device would have to be powerful enough to recharge all the soldier's tactical electronic devices simultaneously, driving up weight and size and offsetting the principal objective benefit. Device integrated pull-out retractable solar chargers are a potential solution if the films can be kept sufficiently thin while retaining the 15% efficiency of current silicon cells – but flexible solutions have fallen far short of this mark.

3. NON IMAGING OPTICS

The second major development area that is central to the VHESC objective is the practical and cost effective application of non-imaging optics. Researchers have discussed the potential application of non-imaging optics to solar cells for decades, but solar cells incorporating non-imaging optics have been relatively large and inappropriate for soldier portable tactical electronic devices. Furthermore, the efficiency of solar cells using non-imaging optics has never exceeded the efficiency of state-of-the-art vertically integrated tandem-stack solar cells. While simple non-imaging optics have been incorporated into automobile headlights for over a decade, the tools and processes to design and cost effectively fabricate small-feature, complex, broad spectrum, non-imaging optics are a recent development.
Fundamental to the VHESC effort is the incorporation of non-imaging optical elements to provide concentration (to increase efficiency and reduce cost), spectral splitting into two or more spectral bands while maintaining high optical efficiency (~93-95%), and a thin form factor relative to the size of the PV elements. Additional practical considerations include good field of view performance, mechanically robust design, and scalability to low cost, large volume manufacture.

These objectives are realizable today because of a variety of developments occurring outside the field of solar power. In the lighting arena, dichroic (spectral splitting) coatings have become practical, efficient, and cost effective through the massive commercial investments stemming from the development and manufacture of MR-16 (track lighting) lamps. More recently, as part of DARPA's High Efficiency Distributed Lighting program, close-coupled fiber-optic lighting has pushed the performance of dichroic coatings to new heights and has integrated the technology with non-imaging complex concentrating optics. In addition, new plastic, glass, and quartz optics manufacturing technologies have dramatically enhanced the cost effectiveness and manufacturing precision with which these optical devices can be fabricated as shown in Figure 1.

The largest key, however, in the non-imaging optical arena is the development of integrated design modeling toolsets that can accurately and robustly be used to design these optical systems. State of the art modeling systems today can incorporate the full range of materials properties, spectral power distributions, source models, target or detector models, manufacturing tolerances, and changes with temperature or illumination conditions, all while close-coupled to a engineering CAD tool design of the parts in question. Variation in median performance of manufactured vice predicted model performance is typically less than 2%. Yield models and Monte Carlo manufacturing models enable the design of the highest performance manufacturable optical system.

Figure 1 – Non-imaging optics are key to several recent advanced lighting technology efforts at DARPA. Shown above left are non-imaging lens designs optimized for operation with high brightness LEDs in a tactical battlefield flashlight application. Several hundred of the flashlights, shown at right, have been deployed to forces in Iraq and Afghanistan to great acclaim. Courtesy of SureFire Inc.

4. NANOSTRUCTURED SOLAR CELLS

The use of nanostructures in photovoltaics offers the potential for high efficiency by either using new physical mechanisms or by allowing solar cells which have efficiencies closer to their theoretical maximum, for example by tailoring material properties. At the same time, nanostructures have potentially low fabrication costs, moving to structures or materials which can be fabricated using chemically or biologically formed materials. Despite this potential, there are multiple and significant challenges in achieving viable nanostructured solar cells, ranging from the demonstration of the fundamental mechanisms, device-level issues such as transport mechanisms and device structures and materials to implement nanostructured solar cells, and low cost fabrication techniques to implement high performance designs. This paper presents the challenges and approaches for using nanostructured solar cells in devices which can approach the thermodynamic limits for solar energy conversion.

Nanostructured solar cells offer several advantages for solar cells including; (1) the ability to exceed a single junction solar cell efficiency by implementing new concepts; (2) the ability overcome practical limitations in existing devices, such as tailoring the material properties of existing materials or using nanostructures to overcome constraints related to lattice matching and; (3) the potential for low cost solar cell structures using self-assembled nanostructures. The multiple potential uses for nanostructures show why there is large interest in these approaches, since they may be able to improve on current technology, whether in high efficiency or lowest $/Wp. Further, since they offer both higher efficiency and low cost, they offer the potential to circumvent both existing efficiency and cost drivers.

While nanostructured solar cells have significant potential to advance photovoltaics, there are also substantial challenges. The efficiency even of precisely grown devices such as MBE-grown structures is presently lower than devices without the nanostructures. Further, experimentally demonstrated advances in nanostructure solar cells using lower cost approaches often rely on absorption/emission mechanisms which do not necessarily correlate to the ability to make devices. Moreover, nanostructured devices do not achieve large absorption (the easiest solar cell parameter to control), much less the collection, voltage, and FF of existing semiconductor devices.

Given these challenges as well as the large number of options and approaches for nanostructured solar cells, it is important to examine nanostructured approaches which may have a practical contribution in the short to medium term and to identify approaches and key challenges in reaching the potential of nanostructured solar cells. This paper examines the options for nanostructured solar cells and identifies key research areas in nanostructures photovoltaics, focusing on components necessary to allow nanostructured PV to contribute to high efficiency devices

5. LOW CONCENTRATION MULTIJUNCTIONS

A cornerstone of the integrated optical/electrical design is the use of low static concentration to realize several important advantages. The theoretical efficiency benefits of low concentration for high efficiency are shown in 2. Since in practice the thermodynamic efficiency can typically not be achieved, we have used a "de-rating" factor of 0.8 for the ratio between an achievable efficiency and the thermodynamic efficiency. This means that in order to achieve >50%, the thermodynamic efficiency must exceed 63%. 2 shows that low concentration (between 10X and 100X) reduces the number of required junctions from 9 to 5 junctions, and also shows that, because of the logarithmic dependence on the efficiency increase and concentration, the majority of the benefit from concentration is captured at low concentration ratios, for which the PV module is deployed like a flat plate module.

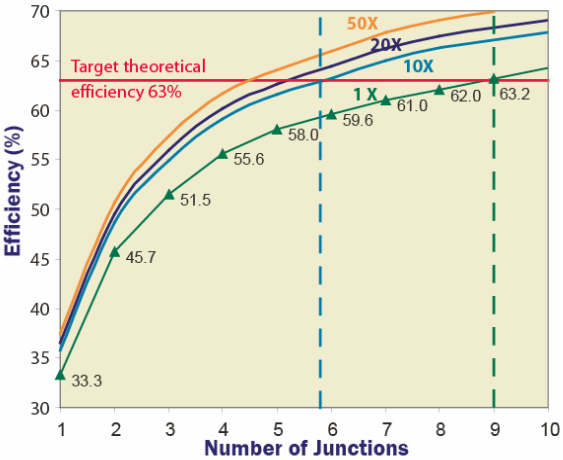

Figure 2: Theoretical efficiency as a function of concentration under AM1.5G conditions.

A second advantage of low concentration is the surface area not used for solar cells enables the design of novel integrated optical and solar cell architectures. The optical design and device architecture of this program is focused on a **Lateral Architecture** which splits the light into spectral components, allowing individual devices to be optimized for each part of the spectrum. This design circumvents many material constraints by avoiding lattice and current matching and by eliminating spectral mismatch losses.

Relaxing constraints related to lattice mismatch and series connection dramatically increases the ability to implement solar cells with ideal band gaps which are manufacturable and affordable. We propose to leverage the high performance and stability of existing best-practices solar cell technology while reducing costs. The program starts with highest-performance solar cell technologies and adds new device architectures and process technologies as they demonstrate **(1) higher performance** at a similar cost or **(2) lower cost** at the same performance. Every significant technical risk is addressed along diversified, competing paths to reduce risk. The flexibility of the architectures allows a wide portal to accommodate new breakthrough concepts such as nanotechnology and biologically-inspired materials for lower cost[3] as well as new high performance concepts.

Optimum band gaps for a 6J solar cell are shown in 3, and demonstrate that the relaxation of series connection and lattice matching enables the development of the solar cell on a silicon platform. The Si platform provides many advantages, but importantly it is the only material capable of presently meeting both the efficiency target (in the wavelength range near its band gap) and the cost targets. The design also allows existing high performance materials to be used for two of the higher band gaps. A final advantage of low concentration is that the solar cell becomes less sensitive to defects, due to the increased operating point of the devices.

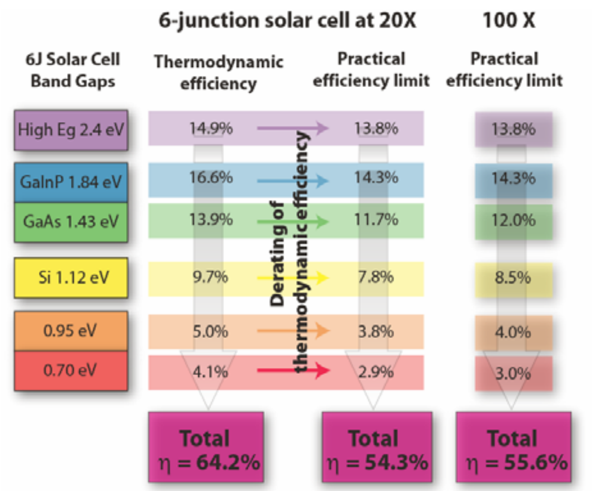

Figure 3: Band gaps for 6J solar cell.

6. INTEGRATED ARCHITECTURES: OPTICAL AND PV

A central novelty of our approach is an integrated optical and solar cell design. By integrating the optical design with the solar cell design, a much broader choice of materials is permitted, allowing high efficiency, the removal of many existing cost drivers, and enabling the inclusion of multiple other innovations. The key optical element is a static concentrator, which is then used in either a lateral or a vertical architecture. To achieve compact and robust packaging, all of our optical concentrator approaches will be of a tiled nature as shown in Figure 4, the design of which will depend on the co-optimization of the optics and cells to achieve maximum conversion efficiency.

Static Concentrators: A static concentrator increases the power density on the solar cell, but does not need tracking, and is deployed and used identically to a 1-sun solar module by using a wide acceptance-angle optical element (typically non-imaging), which accepts light from a large fraction of the sky. Unlike a tracking concentrator, a static concentrator is able to capture most of the diffuse light, which makes up ~10% of the incident power in the solar spectrum. The trade-off for the wider acceptance angle is a lower concentration[4]. If the application allows the module position to be manually adjusted at any point in the year, the maximum concentration increases. Depending on how long the module is to remain in a fixed position, the concentration can range from 10X to 200X.

Lateral Solar Cell Architecture: A key innovation allowed by the use of static concentrators is a lateral solar cell architecture. In the lateral solar cell architecture, additional optical elements are integrated with the static concentrator, to split the solar spectrum into its component colors[5]. Separate solar cells are placed under each color band, and each solar cell can be contacted separately. The lateral solar cell architecture increases the choice of materials for multiple junction solar cells, since it avoids lattice and current matching constraints. Further, since the devices do not need to be series connected, spectral mismatch losses are reduced. Finally, by contacting the individual solar cells with individual voltage busses, the need for tunnel junctions is avoided. Since each material requires unique tunnel contact metallurgy, eliminating tunnel junctions represents a substantial simplification.

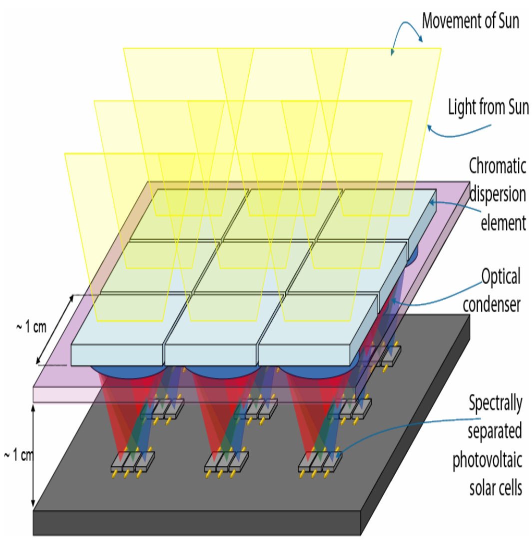

Figure 4: Schematic of the lateral solar cell approach.

The number of spectral regions or bins into which the spectrum is divided is determined by the optical design, with losses increasing as the number of spectral bins increases due to steering the sunlight onto the “wrong” solar cell (i.e., the high energy light falls on a solar cell with a low band gap). To circumvent this, a smaller number of individual solar cells, each consisting of 2 or 3 stacks, can be used. This corresponds to a hybrid of a vertical and lateral approach. In the solar cell device designs, we focus on dividing the light into three regions or bins – high energy, mid-energy and low energy as shown in Figure 5.

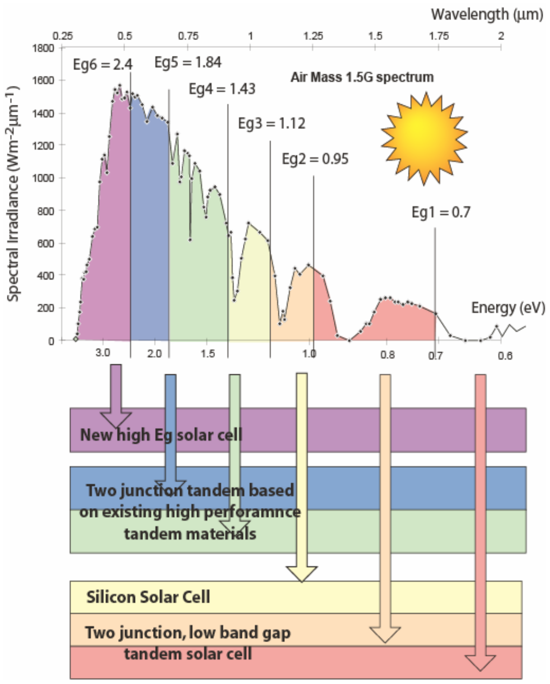

Figure 5: Schematic of the solar cell grouping for the lateral architecture.

7. OPTICAL DESIGNS

In the lateral configuration, a dispersive device is inserted in the optical path (like a diffraction grating or prism) and the light is spread out in angle in the same way as occurs in a spectrometer. Unlike a spectrometer where there is a slit and therefore the size of the source is very small in the direction of the dispersion, the sun subtends a total angle of ~0.5 degrees. This complicates the designs as is described below. Another method of dispersing the light is to use dichroic mirrors where some wavelengths are reflected at a surface and others are transmitted as shown in Figure 6. Commercial examples of dichroic mirrors are cold mirrors where visible light is reflected and infrared is transmitted. A dichroic system serves as the baseline design for the lateral approach. There are ongoing designs for the lateral optics, focusing on issues such as the choice between spherically and or cylindrically symmetric optics, the number of layers in the coating which are compatible with an affordable optical system; many optical designs have achieved over 90% optical efficiency.

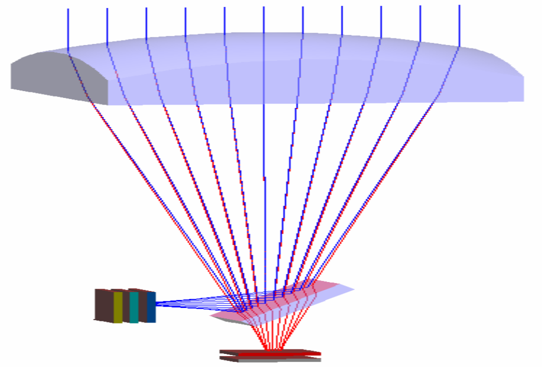

Figure 6: Schematic of the lateral optical system.

8. SOLAR CELL APPROACHES

The integrated optical/solar cell design removes the constraints of lattice and current matching, and hence allows integration of existing high performance technologies such as silicon, GaAs, and GaInP into a high performance device as shown in 3 which has multiple paths to reduced cost. In addition, the development of a 6J tandem requires the development of additional devices and materials. One necessity is the need for high band gap solar cells, since an unconstrained optimized 6J solar cell has the top band gap at 2.4 eV. We utilize the increased flexibility of the design space to propose two other III-V based solar cells to achieve 2.1 eV or above, as well as the III-nitride material system for 2.4 eV solar cells. In addition, two low band gap junctions are needed, which can be implemented either by III-V materials (similar to those used in thermophovoltaic devices), or new approaches based on Ge and Si/Ge.

The flexibility of the optical/electrical design allows the incorporation of multiple types of solar cells, such as the combination of conventional semiconductors with nanostructured solar cells. We capitalize on this by developing nanostructured solar cells, both to address the potential for dramatically reduced cost, as well as to overcome the difficulties of achieving high voltage and efficiency from the low band gap stack. These approaches are described elsewhere[3].

9. COUPLED OPTICAL AND DEVICE MODELS

Detailed device models[7] are used throughout the program as a guide to optimum device designs under appropriate operating conditions. They are used to interpret diagnostic experiments, to predict the effects of proposed cell and system designs and to guide system choices. Appropriate levels of model sophistication are used. In some cases simple minority carrier diode models are sufficient; in others full detailed models which take into account heavy doping effects, degeneracy, graded band gaps, doping profiles, and other effects, not possible to include in simple minority carrier models, are used.

The device models are coupled to optical design tools. For example Figure 7 shows the effect of the changes in a dichroic mirror design upon the output power of a combination of a GaAs cell and a silicon cell where the dichroic mirror splits the spectrum in the vicinity of the GaAs band gap. Three cases are shown: an abrupt transition from transmission to reflection: a 100 nm transition; and a 200 nm transition. These results guide the choice of the location of the transition as well as the impact of changes in the location in the transition upon system performance. An additional benefit of the coupling of the optical and device models in this case is that it guides trade offs in the dichroic filter design. The sharper the transition required the great the number of layers required in the mirror and the higher the cost. Consideration of results like those of Figure 7 allows a trade between expense of the mirror and system efficiency.

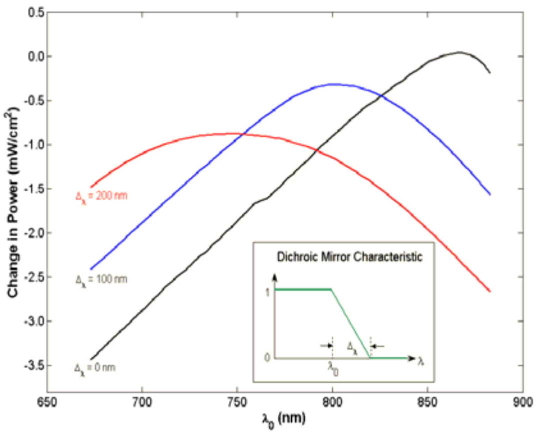

Figure 7: Change in power output relative to the power output with a dichroic mirror with an abrupt transition at the GaAs band edge (872 nm).

10. EFFICIENCY MEASUREMENT METHOD

The efficiency of a concentrator cell is usually measured without regard to the design or performance of the optics[8]. The efficiency of a lens-cell assembly reflects both the optical and cell efficiencies. No standard exists for characterization of the performance of a collection of concentrator cells designed for use under optics that split the spectrum into two or more parts. Consensus standards currently use a global reference spectrum for flat-plate measurements and a direct reference spectrum for concentrator measurements, but a reference spectrum for a low-concentration application has not been defined. Thus, cell performance measurements for the VHESC Program require two new elements: (1) definition of the spectrum relevant to this low concentration application and (2) identification of a methodology for quoting an aggregate efficiency for a set of cells that each use a different portion of the spectrum. These two issues have been addressed, respectively, by (1) choice of the AM1.5 Global spectrum[9], and (2) the solar spectrum is split, mathematically, either by defining dividing wavelengths or by any other method such that the spectral parts sum to give the one-sun reference spectrum. Each cell is then measured in the conventional way using the portion of the spectrum assigned to it. For the results presented here, the spectrum was divided into three sections with the GaInP/GaAs cell measured above the GaAs response (roughly 900 nm) and the GaInAsP/GaInAs cell with light beyond 1100 nm. The solar cells are measured over a range of concentrations, but the VHESC Program reporting conditions were taken as 20 suns.

The quantitative performance measurement of each individual solar cell uses reference cells to characterize the intensity of the solar simulator and a spectral mismatch correction factor to correct for differences between the test and reference cell responses and differences between the test and mathematically calculated reference spectrum relevant to that cell.

The most difficult measurement is for the low-band-gap series-connected tandem solar cell. Accurate measurement of this cell requires adjustment of the incident spectrum so that each of the junctions generates the correct photocurrent. Multi-source simulators provide a means for obtaining the desired spectrum, but today's multi-source simulators do not achieve the concentrations desired for this project. For the low-band-gap tandem, a double-side polished silicon wafer was very helpful toward achieving the correct spectrum in both the multi-source and flash simulators.

Multi-junction solar cells based on all III-V compound series connected devices have achieved 37.9% efficiency at ~ 10 suns and 39% at 240 suns. Wanlass et. al. reported 37.9% at ~ 10 suns for a three-junction GaInP/GaAs/GaInAs cell grown in an inverted configuration[10]. This measurement of high efficiency at relatively low concentrations is consistent with those being pursued in the VHESC Program. King, et al, reported a 39% efficiency for a three-junction GaInP/Ga(In)As/Ge cell at 240 suns and an efficiency of 38.8% at 240 suns for a lattice-mismatched version of the same cell[11]. The 39% efficiency represents a fairly mature terrestrial concentrator version of the three-junction space cells. These concentrator cells are now commercially available with a typical efficiency >30% at 350 suns, demonstrating the progress this technology has made toward implementation in terrestrial solar applications.

11. INITIAL SOLAR CELL RESULTS

GaInP/GaAs tandem cells were prepared using trimethyl gallium, trimethyl indium, phosphine, arsine, and other precursors as described elsewhere[12]. These cells differ from conventional GaInP/GaAs cells because they transmit photons with energy less than 1.4 eV. An undoped GaAs wafer is used, and both the front and back contacts to the device are made on the front side (side with epilayer growth) of the GaAs wafer. This is possible because the active layers of the tandem cell are less than 5 µm thick. The cells use a second tunnel junction and a lateral n-type conduction layer to conduct the current from the back of the layer to the contact pad that forms a frame for the cell.

Light current-voltage (I-V) data are shown in 8 for a GaInP/GaAs cell. An efficiency of 28.4% is seen at 20 suns concentration. The efficiency increases above 29% for concentrations above about 40 suns.

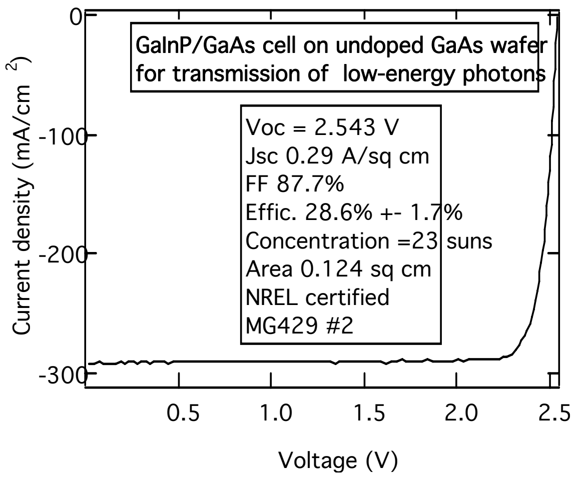

Figure 8: The light I-V curve for a GaInP/GaAs cell with both of the contacts accessible from the front side.

Lattice-matched, monolithic GaInAsP/GaInAs tandem solar cell structures grown on InP substrates are under development for the VHESC Program. The cell structures are grown by atmospheric-pressure metalorganic vapor-phase epitaxy at 620°C using conventional precursors. Series-connected, low-band-gap tandem cells were designed to operate at 20 suns concentration under the global spectrum truncated at a wavelength of 1100nm (i.e., our performance measurement convention for this device). Semi-realistic modeling studies show that the optimum subcell band gap pair is 0.95/0.74 eV if the bottom subcell is constrained to be GaInAs lattice-matched to InP. The subcells in the tandem structure are interconnected using a substantially transparent tunnel junction. The present devices are grown in an inverted fashion on IR-transparent (Fe) InP substrates to allow both contacts to be made on the back surface. The back contact is made to the back of the device mesa, and the front contact is made in the form of a frame around the mesa that contacts a highly conductive window layer on the front-surface of the device. The tandem is illuminated from the opposite side through the InP substrate. An efficiency of 3.5% at 5.7 suns without an anti-reflection coating represents an advanced stage of development for this new technology. The path to higher performance levels includes applying a good-quality, two-layer anti-reflection coating along with design revisions that will enable operation at higher concentration ratios. The assembled solar cell chips are shown in Figure 9.

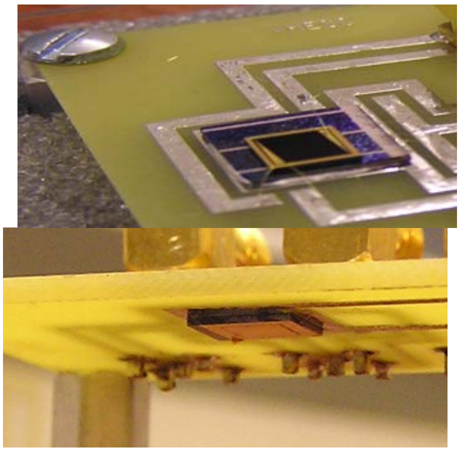

Figure 9: Photograph of the assembled solar cell chips.

12. VALUE OF HIGH EFFICIENCY

The value of high efficiency is manifold. It is a key to low cost, high value applications. High efficiency leads to a lower cost per watt due to increased output from the area related module and system cost. These cost reductions include better materials utilization per Watt and reduced installation costs per Watt. In addition, high efficiency enables larger systems on the same footprint which leads to lower indirect costs per Watt. These costs include design, engineering, site preparation, permitting, inspecting, commissioning and possibly profit.

Using the Solar Advisor Model (SAM) developed by the U.S. Department of Energy's Solar Energy Technology Program, we have calculated that a 50% increase in module efficiency can lead to a 10% reduction in electricity costs before considering any of the other benefits of these efficiency increases. Application of SAM to a 50% ***decrease*** in module efficiency leads to an almost 30% increase in electricity cost. Further details on the value of efficiency will be reported[13].

13. SUMMARY

Photovoltaic energy sources offer a path to solving a critical problem in today's military: portable, renewable, compact power for the soldier in the field. DARPA's Very High Efficiency Solar Cell program is targeting the development of 50% efficient prototype solar cells within the next four years, including the development of pilot scale manufacturing capabilities and the delivery of 1000 prototype units each at 0.5 W peak power and 10 cm^2 aperture area. Key to success in this development is a team-based approach that integrates these new technology opportunities within a larger, broader, diverse group that retains a solid grounding in PV solar cell technology. This influx of new ideas and new capabilities, and more that will follow, are essential to the next generation of PV solar cell technology breakthroughs.

The VHESC team is made up of 21 institutions, led by the University of Delaware. The team includes BP Solar, Emcore, Corning, Blue Square Energy, DuPont, SAIC, Fiberstars, ORA, LightSpin, Purdue, Harvard, MIT, Georgia Tech, UCSB, California Institute of Technology, University of California Berkeley, the University of Rochester, and the National Renewable Energy Laboratory (NREL). This wide spectrum of team members from academia, small and large industry, and national laboratories provide the program the ability to develop technology, integrate technology into a common design, and develop a path to scaleable production.

14. ACKNOWLEDGEMENTS

The research reported in this document was prepared through participation in an Agreement sponsored by the Government under DARPA/ARO Agreement W911NF-05-9-0005. The views and conclusions contained in this document are those of the author(s) and should not be interpreted as presenting the official policies or position, either expressed or implied, of the U.S. Government unless so designed by other authorized documents. Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation hereon.

NREL's portion of this work was completed under Contract No. DE-AC36-99GO10337 with the U.S. Department of Energy.

14. REFERENCES

1. Douglas Kirkpatrick, Eric Eisenstadt, Amanda Haspert, *DARPA's push for photovoltaics,* Proc. 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion, May, 2006, Waikoloa, Hawaii(to be published).
2. Allen Barnett, Christiana Honsberg, Douglas Kirkpatrick, Sarah Kurtz, Duncan Moore, David Salzman, Richard Schwartz, Jeffrey Gray, Stuart Bowden, Keith Goossen, Michael Haney, Dan Aiken, Mark Wanlass, Keith Emery, *50% Efficient solar cell architectures and designs,* Proc. 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion, May, 2006, Waikoloa, Hawaii(to be published).
3. Christiana Honsberg, Allen Barnett, Douglas Kirkpatrick, *Nanostructured solar cells for high efficiency photovoltaics,* Proc. 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion, May, 2006, Waikoloa, Hawaii(to be published).
4. C. Minano, and A. Luque, "Limit of concentration under extended nonhomogeneous light sources," *Applied Optics*, 22, 17, 2751-60, (1983).
5. A. G. Imenes and D.R. Mills, "Spectral beam splitting technology for increased conversion efficiency in solar concentrating systems: a review," *Solar Energy Materials & Solar Cells,* 84, 19-69, (2004).
6. T. Trupke, and P. Wurfel, "Improved spectral robustness of triple tandem solar cells by combined series/parallel interconnection," *Journal of Applied Physics*, 96, 4, 2347-51, (2004).
7. S. M. Durbin and J. L. Gray, "Numerical Modeling of Photon Recycling in Solar Cells", IEEE Trans. Electron Devices, Vol. 41, No. 2, pp. 239-245, 1994.
8. K. Emery, M. Meusel, R. Beckert, F. Dimroth, A. Bett and W. Warta, "Procedures for Evaluating Multijunction Concentrators," *Proc. 28th IEEE Photovoltaic Specialists Conf.*, Anchorage, AL, Sept. 15-22, 2000, pp. 1126-1130, IEEE, New York, 2000.)
9. ASTM Standard G173, "Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface," Amer. Society for Testing Matls., West Conshocken PA, USA
10. M. W. Wanlass, S. P. Ahrenkiel, D. S. Albin, J. J. Carapella, A. Duda, K. Emery, J. F. Geisz, K. Jones, Sarah Kurtz, T. Moriarty, and M. J. Romero, "GaInP/GaAs/GaInAs Monolithic Tandem Cells for High-Performance Solar Concentrators," Proc. International Conference on Solar Concentrators for the Generation of Electricity or Hydrogen, May 1-5, 2005, Scottsdale, AZ, USA
11. R. R. King, D. C. Law, C. M. Fetzer, et al., in *20th European Photovoltaic Solar Energy Conference*, Barcelona, Spain, 2005)
12. K. A. Bertness, S. R. Kurtz, D. J. Friedman, et al., Appl Phys Lett **65**, 989 (1994).
13. Ming-Jay Shiao and Allen Barnett *(to be published).*