Very High Efficiency Solar Cells

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ABSTRACT: A major goal of the PV industry is to develop high-efficiency, low-cost solar cells and devices. Recently, several approaches have been proposed for approaching the thermodynamic limit of solar energy conversion. It has been shown that the practical efficiency of different approaches can be substantially different, regardless of the fact that the theoretical efficiencies may be similar. A broad approach, combining select components and techniques from different technologies introduces the valuable advantage of expanding the range of possible materials and processes. A consortium with around 20 contributors, led by DuPont and the University of Delaware, with substantial funding from DARPA, aims to create devices that operate at 50% efficiency in production for $1,000 m^2. This aggressive goal is realisable because of recent rapid advances in materials processing, non-imaging optics, and solar cell architectures. ANU has recently joined the team, to work on silicon cells for tandem stacks. An innovative optical design, integrated with the cell design, offers the possibility of optimising the optics, the cells, and the circuit topology to produce an ultra- high efficiency device.

1. INTRODUCTION

For decades crystalline silicon has been the material of choice for photovoltaic (PV) modules, and currently accounts for 90% of the PV market. Silicon-based solar cells dominate because of high cell efficiencies compared with alternative materials, proven long-term cell and module reliability, the abundant and non-toxic nature of silicon, and the ability of the silicon-based PV industry to share technology, skilled people, and infrastructure with the silicon-based integrated circuit industry.

Silicon is the 2nd most abundant element in the Earth's crust. It is cheap to produce, but expensive to purify to the levels required for the electronics and PV industries. Various solutions to the silicon-supply and purification cost problem are being investigated, including the use of non-silicon PV materials, concentrator PV systems, solar cell designs that can utilise mid-purity silicon, and thin crystalline silicon solar cells that use less silicon.

In order for silicon-based PV technology to compete economically with conventional sources of electricity one of two scenarios must be established: either conventional electricity must be supplied at its true cost – including the cost of environmental damage, or the cost of solar module production must be reduced to around US$1 per watt with module efficiencies around 15%. But silicon-based technology, particularly single junction silicon technology, is approaching its practical efficiency limits. Further gains on this front will be incremental.

Cost reductions have, until recently, largely been achieved via the normal mechanism associated with the growth and maturing of an industry, as demonstrated by the learning curves of Parente et al. (2002). However, the rapid growth in the PV market has caused shortages in the supply of the hyper pure electronic-grade silicon upon which the industry relies. One response has been to produce cells from thinner wafers, although this is limited by ingot sawing technology and also poses significant wafer handling issues. Another response has been for research to focus on other methods for reducing the consumption of silicon: the thin-film silicon technologies such as those under development at Fraunhofer ISE; Reber (2005); ISFH: Terheiden (2006), and UNSW; Aberle (2006); and SLIVER Technology, Weber (2001), for example.

A novel approach is required in order to break through the fundamental barriers that limit conventional approaches. The VHESC (Very High Efficiency Solar Cell) Program is one such novel approach.

1.1. High efficiency approaches and limitations

One method for approaching thermodynamic limiting efficiencies, ranging from 68% to 87% depending on the solar spectrum and the degree of concentration used, uses multiple junction tandem devices under concentration. The single largest loss mechanism for any PV technology is spectral mismatch. Photons below the bandgap are not absorbed; and the excess energy of absorbed photons over and above the bandgap is also lost.

The assumptions made for detailed balance analysis include (i) a standard solar spectrum; (ii) a single photon generates a single electron-hole pair; (iii) a single bandgap in the cell; and (iv) constant temperature across the cell. Any ultra-high efficiency approach must circumvent at least one of these four assumptions.

Consideration of the above shows there are five basic approaches to ultra-high efficiency devices, Honsberg (2005):

1. Multiple junction solar cells;
2. Multiple spectrum solar cells, (where the solarspectrum is changed into a different spectrum, within the bounds of conservation of energy);
3. Multiple absorption path solar cells (for example with two photons being absorbed to produce a single electron-hole pair, or two electron-hole pairs produced by the absorption of a single photon);
4. Multiple energy level solar cells, (more than one quasi-Fermi level separation);
5. Multiple temperature solar cells (involving the extraction of energy from variations in lattice or carrier temperature); and
6. AC solar cells, which have the potential for high efficiencies, but require Terahertz devices functioning as rectenna to be developed.

The theoretical efficiency limit for each of the ultra-high efficiency approaches is similar, but the physical mechanisms and practical efficiency limits for each are substantially different. For example, the efficiency of a multi-junction device can be increased by increasing the number of junctions. However, this pre-supposes that high quality materials with the correct band gap, and well-understood technologies, are available. This is not the case, so a practical approach to ultra-high efficiency devices must avoid the requirement for a large number of ideal materials and processes.

Spectral transformation converts the broad solar spectrum to a narrow spectral range optimised for the cell and optical system. This is usually performed externally to the cell, so the technology has a potential low-cost application to conventional PV.

Conventional PV has the fundamental limitation of a single electron-hole pair generated from each absorbed photon. This basic limitation can be circumvented by achieving two-photon absorption (TPA), where two photons produce a single elctron-hole pair, or by impact ionisation (Auger generation) where a single high-energy photon produces multiple electron-hole pairs. Measurements of these absorption processes have been performed in bulk materials by Kolodinski at. al (1993), but nanostructured materials are required in order to produce a significant effect. For example, Schaller et al (2004) reports close to 100% impact ionisation and high two-photon absorption with nano-structured materials. Either, or both, of these processes is insufficient to ensure high cell efficiencies: the important factor is that these processes produce a quantum efficiency substantially greater then one.

With multiple energy level devices, energy loss via the spectral and band gap mis-match is circumvented by the introduction of extra energy levels, allowing the efficient absorption of photons with differing energies. There are two main processes: localised energy levels or “quantum well solar cellls” and continuous mini-band energy levels or “intermediate band solar cells” – both named after the first solar cell to propose this approach. Both processes are similar in that their function is to produce multiple light-gernerated quasi-Fermi levels in the device. However, the physics of the two approaches - in particular the transport of carriers, is quite different.

Solar cells can use temperature differentials within a single device to generate power. Temperature differentials may arise from variations in the physical lattice temperature, but in a functioning cell it is easier to maintain a temperature differential between hot carriers and thermailsed carriers. An attractive advantage of the multiple temperature approach is that a thermal converter allows higher theoretical efficiencies for a given high concentration structure. Although this approach allows a theoretical efficiency of 66% with three energy levels, the physical effect of thermal interactions have yet to be demonstrated.

If the photon is treated as an electromagnetic wave, the signal produced by the interaction of the wave with an antenna can be rectified with a diode. There are fundamental physical problems with this concept, including reciprocity, the broad solar spectrum, the incoherent nature of light from the sun, and the technical challenge of operating in the Terahertz region.

Any of the above approaches can theoretically be used to exceed the Shockley-Queisser limit in a single solar cell. Practical considerations limit the potentially realisable efficiency of these devices to about 50% at one sun and perhaps 65% at high concentration. Present, state-of-the-art triple-junction cells have efficiencies of about 41%. It is evident that ultra-high efficiency devices must use more than one cell or one junction, Honsberg and Barnett (2005). However, as the number of pn junctions increases, materials requirements for these advanced cells introduce major difficulties. Optimised materials, ideally lattice-matched and possibly also metamorphic, must be obtained for each junction. Further, as the number of junctions increase, the optimum value of the upper band gap increases, requiring the development of material systems not presently used in tandems.

Since each of the above broad approaches offer potential advantages, it seems reasonable to conclude that the optimum ultra-high efficiency solar cell will consist of a hybrid between existing tandem and novel concept approaches.

1.2. Background to the VHESC Project

In November 2005 it was announced that a broad consortium led by the University of Delaware (USA) would receive substantial funding, with the bulk of the money coming from the Defence Advanced Research Projects Agency (DARPA), to reach 55% solar cell efficiency by the end of 2009. The team leaders are Allen Barnett and Christiana Honsberg, who are well-known in the international photovoltaic community.

The project title is Very High Efficiency Solar Cells (VHESC) Program. The VHESC team is made up of around 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 list comprises most of the top entities in the field of photovoltaics in the USA. ANU has recently joined the team, to work on silicon cells for tandem stacks.

1.3. Device architectures and designs

The central innovation in the VHESC project is the integration of the design of the cells, the optics, and the electrical interconnects, thus increasing the the design space in terms of materials, device structures, and manufacturing technology. One of the key requirements of the VHESC Program is the formulation of a *manufacturable* ultra-high efficiency device. The integrated approach provides many benefits, including higher theoretical efiiciency limits; makes possible new architectures which are not limited by existing materials and costs trade-offs; optimised component device designs, reduced spectral mismatch losses; and broader flexibility in materials choices.

One very important feature of the integrated design is the use of low static concentration to realise several important advantages. A realistic goal of 80% of the theoretical thermodynamic efficiency has been set. This means that in order to achieve greater than 50% device efficiency, the thermodynamic efficiency must exceed 63%, Barnett (2006). Because of the logarithmic dependence of the efficiency increase on concentration, the benefit is maximised for low concentrations.

A further advantage of low concentration, as opposed to full-cover, one-sun, flat-plate devices, is that the area not used by cells can be used for novel optical arrangements. Barnett (2006) identifies two main optical design and device architectures: (i) the lateral architecture, which splits light into spectral components, allowing component devices to be individually optimised, avoiding many material constraints by eliminating the requirement for lattice and current matching, and eliminating spectral mismatch losses; and (ii) the vertical architecture, which uses an independently contacted vertical junction stack that increases material choice flexiblity, avoids the requirement for current matching, and also avoids spectral midsmatch losses. Relaxing lattice mismatch constraints and eliminating series connections increases the range of choice for affordable and manufacturable band gap materials and increases the flexibility of architecture. Another advantage of low concentration is that the solar cell becomes less sensitive to defects such as shunts because of the increased operating voltage of the devices.

1.4. Integrated optical and solar cell architectures

The VHESC Program integrates the optical and cell designs; permitting a broad choice of materials, the removal of several conventional cost drivers, and opening the way for the inclusion of other innovations such as the static concentrator. In order to realise a compact and robust package, a tiled optical concentrator has been chosen.

The form of the static concentrator is such that it increases the power density on the solar cell, without the need for tracking, and can be deployed and used in a manner identical to that of a one-sun module by using a non-imaging, wide acceptance angle optical element. One advantage of this approach is that a non-tracking concentrator can capture most of the diffuse light, which makes up around 10-25% of the power in the solar spectrum. The wider the acceptance angle, the lower the concentration that can be achieved, Minano (1983). If the application allows the module position to be manually adjusted, the maximum possible concentration ratio increases. Depending then on the time between adjustments, the concentration ratio can range from aroun 10-suns up to about 200-suns.

A suitable choice of static concentrator allows additional optical elements, used to split the spectrum into appropriate segments, to be integrated with the static concentrator optics. Separate solar cells, contacted separately and optimised for the purpose, can be placed under each spectral segment, providing the means for reducing spectral mismatch losses. This lateral solar cell architecture also increases the range of choice for materials for tandem cells since it eliminates the requirement for lattice matching as well as current matching. Because individual solar cells can be contacted with individual voltage buses tunnel junctions can be avoided, providing a substantial simplification since, in the absence of this simplication, each cell material would require a unique tunnel contact metallurgy, as well as lattice matching.

Spectral mismatch losses decrease as the number of spectral segments increases. But losses due to incorrect light guiding with static concentrators increases as the number of spectral segments increases. A hybrid vertical-lateral approach allows the best of both worlds by utilising a smaller number of individual solar cells, each consisting of two or three stacks.

A similar approach could be taken with a vertically-integrated device in which the solar cells can be individually contacted. Because of the static concentrator, the greater portion of the surface is free of solar cells, allowing adequate room for forming electrical contacts to individual junctions.

There are several possible options for optical design. These include a diffraction grating or prism in the optical path to provide spectral spread to the light beam, but because the sun subtends an angle of approximately half a degree this introduces some complicaitons. Alternatively, dichroic mirrors can be used to split and direct spectral components, with a choice between spherically or cylidrically symmetrical optics. Optical designs so far have achieved over 90% optical efficiency, Barnett (2006).

The integrated optical and cell design eliminates lattice and current matching constraints, allowing the use of existing high performance technologies such as silicon, GaAs, and GaInP in configurations with multiple pathways to reduced system cost. A six-junction tandem requires the development of additional devices and materials, particularly high band gap solar cells since an unconstrained optimised six-junction solar cell requires an upper band gap of 2.4 eV. This can be provided by III-nitride material system, with the possibility of two other III-V based solar cells for the 2.1 eV cells. Further, two low band gap junctions are needed. These can be implemented with III-V materials similar to those used in thermophotovoltaic (TPV) devices, or with new approaches based on Ge and

Si/Ge, Barnett (2006).

The flexibilty provided by the lateral solar cell architecture and the integrated optical electrical design allows multiple types of cells, including combinations of conventional cells and nano-structured solar cells, to be incorporated into the system. Detailed modelling has been undertaken in order to optimise system components, including performance and cost trade-offs.

1.5. Efficiency measurements

The efficiency of an optical component and a cell is a convolution of the efficiencies of both the cell and the optical system. Presently, no standard exists for performing efficiency measurements of systems using split-spectrum concentration, but consensus standards use a global reference spectrum for flat plate measurements, and a direct reference spectrum for concentrator measurements. In order to quantify efficiency measurements for the VHESC Program in terms of the relevant spectrum and methodology, the AM1.5 Global spectrum has been chosen, and the spectrum is split by defining bounding wavelengths such that the sum of the spectral components produce the one-sun reference spectrum. Efficiency measurements of individual cells use reference cells to characterise the intensity of the solar simulator, with a spectral mismatch correction factor applied to the test cell, Barnett (2006).

2. ANU VHESC COMPONENT SILICON SOLAR CELL FOR TANDEM STACKS

The contribution of CSES at ANU to the VHESC Program is to manufacture high performance Silicon concentrator cells in small numbers. The ANU Silicon cell will be one of 6 cell types, each of different material (eg GaAs, InGaAs, silicon, GaN, and so on), in tandem packages. Each material will harvest a different part of the solar spectrum, and, as explained above, can be independently wired. Other consortium members are responsible for cells fabricated on other materials.

Sunlight with power of around 2 W/cm^2 is incident on the top of the package. GaAs and other cells absorb much of this light. Photons with an energy less than 1.42 eV will be transferred to the Si cell. The power of the light incident on the silicon will be about 0.7 W/cm^2. The light incident on the Si cell will be in the form of a spot, approximately 2 mm in diameter, which will wander in a track a few millimetres long as the sun moves.

Silicon is a relatively poor absorber of light in the energy range from 1.1 to 1.42 eV. A long light path length of light for wavelengths in the range 875-1100nm is required in order to have a reasonable efficiency of conversion in this weak-absorption range. Absorption can be enhanced by using a back surface reflector or by texturing the silicon. However, photons with an energy less than 1.1eV must propagate through the Si cell to underlying low bandgap cells. Therefore a back surface reflector cannot be used. Similarly, there are problems with texturing, since about half of the light escaping from the textured cell would propagate upwards, towards the high bandgap cells, rather than downwards, to the lower bandgap cells. Additionally, the very long optical path lengths produced by good texturing increases free carrier absorption, which reduces the availability of photons for the underlying low bandgap cells.

Generally, a low bandgap InGaAs cell will have a Voc*FF product about 60% as good as silicon, and will therefore be less effective than silicon at converting a photon to electrical power. However, if a particular silicon cell design results in an internal quantum efficiency of less than about half for a particular photon energy range, in this case for photons with energy around 1.1 eV, then it is better to allow such photons to propagate to the underlying low bandgap cells. Another option to increase the absorption of the silicon is to increase the cell thickness. Provided that a high internal quantum efficiency (IQE) can be maintained, this will increase the current. However, the open circuit voltage will be reduced because of the increased volume available for recombination. The extent of open circuit voltage reduction due to volume recombination depends on the cell diffusion length and the relative proportion of surface recombination.

The removal of the blue end of the illumination spectrum from the silicon cell means that the distribution of photon absorption is far more uniform than is the case for conventional sunlight, although most of the minority carriers will still be created in the illuminated front half of the cell. The more uniform photon absorption distribution means that a poor ratio of diffusion length to cell thickness, in the case of a conventional cell design, will produce a larger deleterious impact on IQE. Our modelling suggests that an IQE above 99% will be achieved if the diffusion length is above about 4 times the cell thickness, for a conventional cell design. Cells with a junction on both surfaces can be twice as thick for the same IQE.

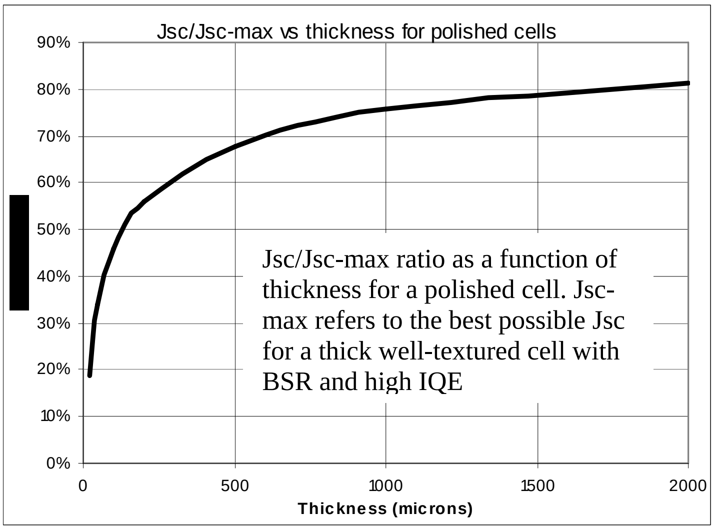

Figure 1 Jsc/Jsc-max ratio for polished cell.

Without the option of texturing, or the inclusion of a BSR, there is a difficult balance between long optical path length and the requirements for low volume recombination, high IQE, low free carrier absorption (FCA), and low resistive losses.

Free carrier absorption of light, whereby free electrons and holes absorb light without generation of new electrons and holes, is a significant problem for thick and highly doped material used to minimise resistive losses. For example, the free carrier absorption loss in a 1mm thick 0.1 ohmcm wafer (sheet resistance 1 ohm/sq) at 1100 and 1400nm is about 9% and 14% respectively. However, for sheet resistances of a wafer of 10 ohm/sq or higher, free carrier absorption will be less than 1%.

FCA in highly doped diffusions is more serious than in a wafer of the same sheet resistance, because mobility is low in highly doped regions, leading to relatively high doping levels to achieve a given ohm/sq value. In general, driving-in the diffusion reduces the FCA loss for a given sheet resistance since average mobility will be higher, and hence the required doping dose will be lower. FCA in diffusions is not too serious provided that sheet resistance can be kept above 20 ohm/sq.

Most of the photons with an energy less than 1.1 eV must pass through the Si cell to an underlying InGaAs cell. Since texturing and light trapping would inhibit transfer of light to underlying cells, the silicon cell must be very thick to maximise absorption by the light in the energy band allocated to the silicon cell.

In the VHESC device, the cells will be surrounded by an optically thick n=1.4 medium. This means that the effect of an oxide AR coating vanishes, so alternative AR coatings will be utilised. Since the incident spectrum has a relatively narrow wavelength range, it is possible to devise a very effective AR coating for the silicon cell.

One possible design for the silicon component of the VHESC Program is a vertical multijunction (VMJ) configuration, which allows a cell package to be arbitrarily thick in order to maximise light absorption, while still maintaining high IQE. High IQE can be maintained by performing phosphorus diffusions over nearly the entire surface of each p-type subcell.

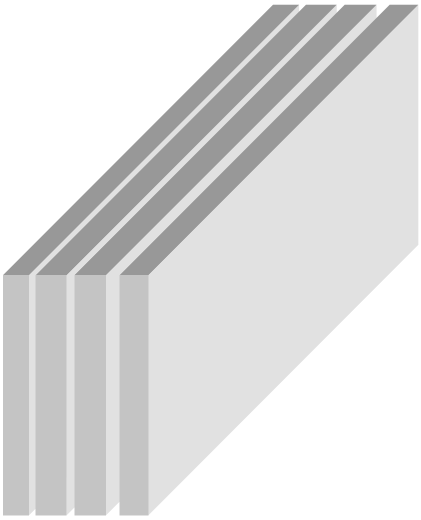

Figure 2. A VMJ cell stack

The VMJ design also allows relatively easy extraction of carriers to minimise resistive losses, and allows the removal of contacting metal from the optical path. The disadvantages compared with a conventional design are the increased surface area, which results in an increased surface recombination rate, the increased junction area, which results in an increased junction recombination rate, and the increased volume recombination arising from the relatively large volume of silicon deployed.

Prototype working cells have been successfully fabricated and tested under the CSES flash tester, which allows cell performance under a range of different illumination intensities to be measured.

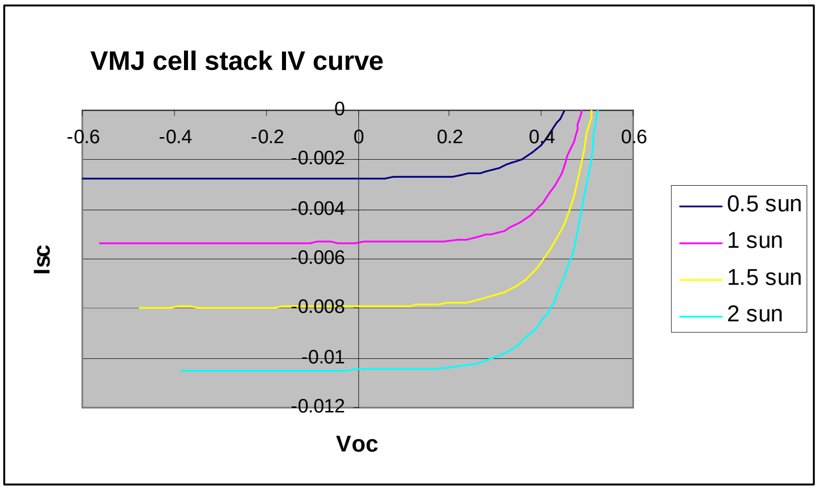

Figure 3 Prototype VMJ cell stack characteristics

Performance measurements have not been conducted under correct spectral conditions, or with the correct aperture.

The indicative V_{oc}, I_{sc}, and fill factor of the best package is 6mA, 500mV and 62%. The efficiency when illuminated by 2W/cm^2 sunlight through a GaAs filter and a 1.9mm diameter aperture is approximately 3%. The ideality factor, n, of about 2.0 suggests that substantial junction recombination is present, arising from the large area of p-n junction, coupled with reduced minority carrier lifetime. This also results in a reduced V_{oc}, and a substantially reduced fill factor. There is also significant series resistance, arising from compromises in the design of the cell.

An image of the first VMJ cell stack is shown in Figure 4. It is expected that greatly improved efficiencies will be obtained in the future as the cell design and processing is implemented.

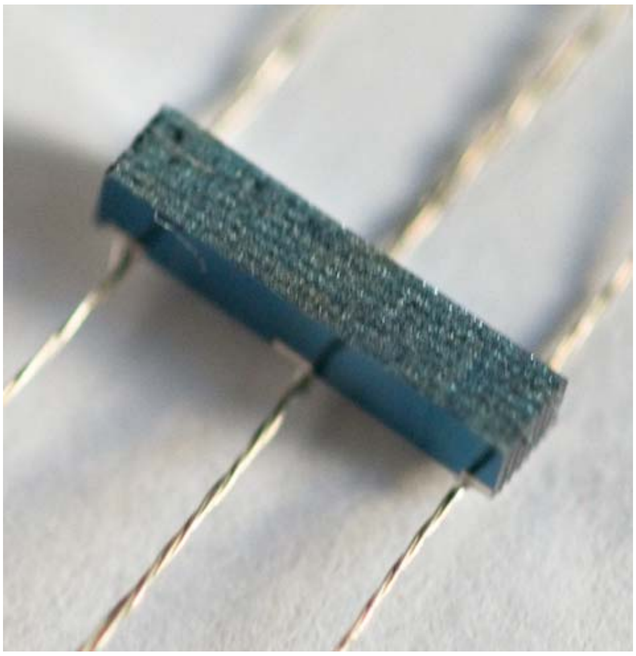

Figure 4. A prototype VMJ stack

3 CONCLUSION

The VHESC Program has progressed steadily since 2005, and has recently set a new record with a 42.8% combined solar cell efficiency. This is a significant step, particularly in view of the small and portable architecture used, and the short development time of 21 months. Given that the devices are potentially less than one centimetre thick, require no sophisticated tracking, and operate at a low concentration of around 20-suns, this record is a major step towards the goal of 50% efficiency.

The Program leader, Professor Allen Barnett, credits the early success to the team approach taken to solve the problem. He says having the companies, universities, and national laboratories in the consortium has produced a “virtual laboratory” which has provided access to a broad range of capabilities in terms of expertise and equipment.

Professor Barnett believes the 50% efficiency mark is just the beginning, with the best inventions yet to come. The goal of the newly-formed DuPont-University of Delaware VHESC consortium, of which

ANU is a member, is to create devices that operate at 50% efficiency in production. With fresh funding, and the cooperative efforts of the DuPont-UD consortium, Barnett anticipates that the new high-efficiency solar cells could be in production by 2010.

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