Photovoltaics take a load off soldiers

A US consortium is aiming to smash the solar-cell efficiency record with a radical design that uses a lateral architecture and a dispersive concentrator. If they are successful, soldiers will be freed from a 20 lb load of spare batteries. **Richard Stevenson** reports.

A consortium of 22 institutions is aiming to develop 50% efficient solar cells that could provide a replacement for spare batteries, which account for one-fifth of a soldier's carrying load. The team is led by the University of Delaware and includes Emcore, BP Solar, DuPont, Corning, Blue Square Energy, SAIC, Fiberstars, ORA, Lightspin, Purdue, Harvard, Massachusetts Institute of Technology, Georgia Tech, the University of California Santa Barbara, California Institute of Technology, the University of California Berkeley, the University of Rochester, the University of New South Wales, Carnegie Mellon University, Yale and the National Renewable Energy Laboratory.

Think of solar cells and you probably think of high-tech devices powering satellites or arrays of devices in sunny climes generating electricity for the national grid. But the US Defense Advanced Research Projects Agency (DARPA) has another application in mind. It believes that solar cells can be used to recharge the batteries that power a soldier's radio, night vision goggles, GPS navigation system and other electronic gadgets, and it is supporting a program that will receive up to $53 million to develop photovoltaics with the required efficiency.

The main disadvantage of batteries is their weight. Despite advances in technology, spare batteries still account for one-fifth of a soldier's 100 lb battlefield load, which includes a pack, weapon, protective gear and a suite of electronic gadgets. Although these batteries are used to operate devices that can save lives, the weight encumbers movement and increases vulnerability.

Batteries also have to be replaced regularly because a 20 lb stock will only last three to seven days. This is a significant logistical task, requiring military aircraft to transport batteries to airfields and then helicopters or ground transport to ferry them on to where they are needed. The cost in people, material and transport assets to keep this supply chain filled is staggering, says DARPA program manager Douglas Kirkpatrick.

Although the battery's weight and lifetime are major drawbacks, solar-cell technologies are not efficient enough to offer viable alternatives. The space available on the soldier's gadgets for a solar cell varies, but it is too risky to fix cells on equipment with more space and use them to power other gadgets because damage to an individual piece can have knock-on effects. So instead each gadget must have its own cell, which places an upper limit on the size of the solar panel of 10 cm^2.

Silicon falls well short of this 10 cm^2 criteria. If a silicon solar cell were used to recharge tactical battlefield flashlights over eight-hour periods (and other devices used by soldiers, which have similar requirements), it would need an active area of 33 cm^2 and an efficiency of 15%. Today's best triple-junction cells can get closer to the efficiency target with cells approaching 40% – although they require 500× concentrations that are not suitable for portable applications – but a hike in efficiency to 50% is needed to meet the 10 cm^2 target.

To reach this goal, DARPA launched its Very High Efficiency Solar Cell (VHSEC) program, which began in November 2005. Led by Allen Barnett from the University of Delaware, this project is using multiple-junction solar cells and involves contributions from 21 additional institutions including Emcore, BP Solar, Corning, the National Renewable Energy Laboratory and various high-profile US universities.

The team, which Barnett describes as the "broadest high-capability group established in the field", aims to deliver 1000 prototype 10 cm^2 modules with a minimum efficiency of 50% and an output power of 0.5 W

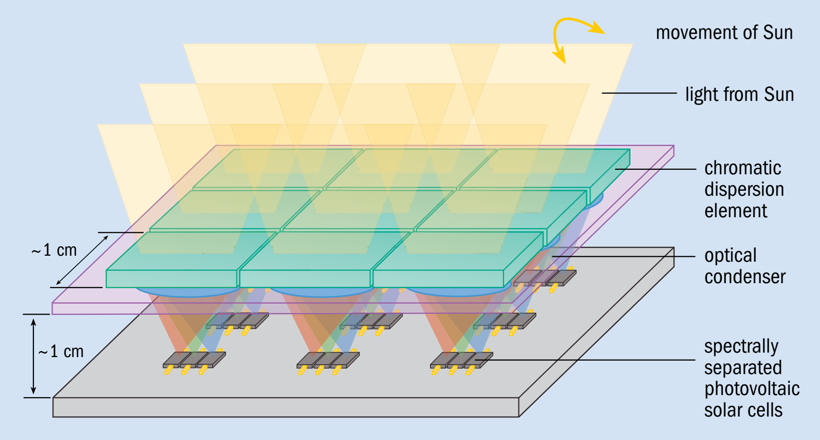

Fig. 1. The use of a specially designed concentrator and a lateral solar-cell architecture holds the key to producing efficiencies in excess of 50%. Incident solar light is split by the concentrator and directed onto three separate solar cells – for high-energy, medium-energy and low-energy photons. The concentrator design uses tiled elements because these enable compact and robust packaging.

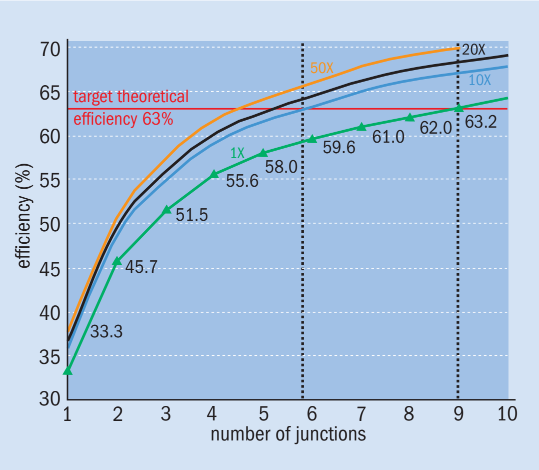

Fig. 2. Improvements to solar-cell efficiencies can be produced by increasing the power of the concentrator and the number of junctions in the cell. Practical solar cells can probably only deliver four-fifths of their theoretical limit, so a theoretical efficiency of more than 63% is needed to produce a working efficiency of 50%. For this efficiency at least six junctions are required, alongside a 10× or greater concentrator. The focusing power of the concentrator also boosts the solar-cell efficiency, by increasing the current in the device, which in turn drives the voltage up. "You don't get more current – in fact you lose some optically – but you pick it up in the voltage," explains Allen Barnett from the University of Delaware.

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> **Douglas Kirkpatrick,** DARPA

by 2009. The weight of these cells is not an issue: "Even if it was made out of solid metal it would weigh less than one set of spare batteries," says Kirkpatrick. Cost is not a big issue either because even if the price for solar material was $\$10\,000\ \mathrm{m}^{-2}$, a $10\ \mathrm{cm}^2$ cell would cost $10, which is a fraction of the total cost of a soldier's equipment.

Barnett believes that the 50% target cannot be met by just making refinements to the most efficient photovoltaics ever built. Instead, a radically different approach is needed that combines a lateral architecture, which was first proposed many years ago, with non-imaging concentrators that disperse and focus various portions of the incident spectrum onto different cells (see figure 1). "The real advantage of the lateral design is that it brings plug-and-play to solar photovoltaic technology," explains Kirkpatrick. "You can swap improvements in and out without starting from scratch."

The concentrator's design is based on work that Kirkpatrick carried out for DARPA's high efficiency distributed lighting program and uses dichroic coatings to manipulate and direct the incident radiation. According to Barnett, Kirkpatrick's idea was confronted with skepticism: "The optics-based researchers gave him all the reasons why it wouldn't work." For the concentrator to be effective, 90% of the photons have to land on the correct solar cell. "We have exceeded 90%", enthuses Barnett, "and there's a chance we could go over 95%, which would be very exciting."

The concentrator is fixed and a wide-acceptance-angle optical element captures a high proportion of diffused light, which typically makes up one-tenth of the incident power in the solar spectrum. Tracking concentrator designs were also considered but DARPA thinks that they are too risky to use in the desert, where many of the US Army's soldiers operate.

The concentrator used by Barnett and his team delivers a lot of freedom in terms of the number of cells that can be used in the design. However, theoretical calculations have determined a constraint that at least six junctions are required to make a practical device operating at over 50% efficiency (see figure 2). These six junctions could be fabricated as six separate cells. However, this is not the most efficient way to do it because a higher proportion of the light is steered onto the "wrong" cell as the number of spectral bins increases. So Barnett's team is using a design that divides the radiation into just three bins – a high-, mid- and low-energy bin – and focuses them onto different solar cells that have up to three junctions (see figures 1 and 3). These solar cells can be independently contacted, which avoids the current-matching issues that complicate conventional multi-junction cells. Lattice-matching constraints are also relaxed, which allows more freedom in the choice of bandgap for the device. The architecture is also very flexible because improvements made to one type of cell can be implemented without any detriment to the other cells.

Working with the new design rules

Part of the project involves establishing the best material combination for each of the three cells. Nitrides are being investigated for the high-energy cell and a GaInP/GaAs tandem design for the mid-energy cell. Silicon is being used as part of the low-energy triple-junction cell, alongside materials with bandgaps of

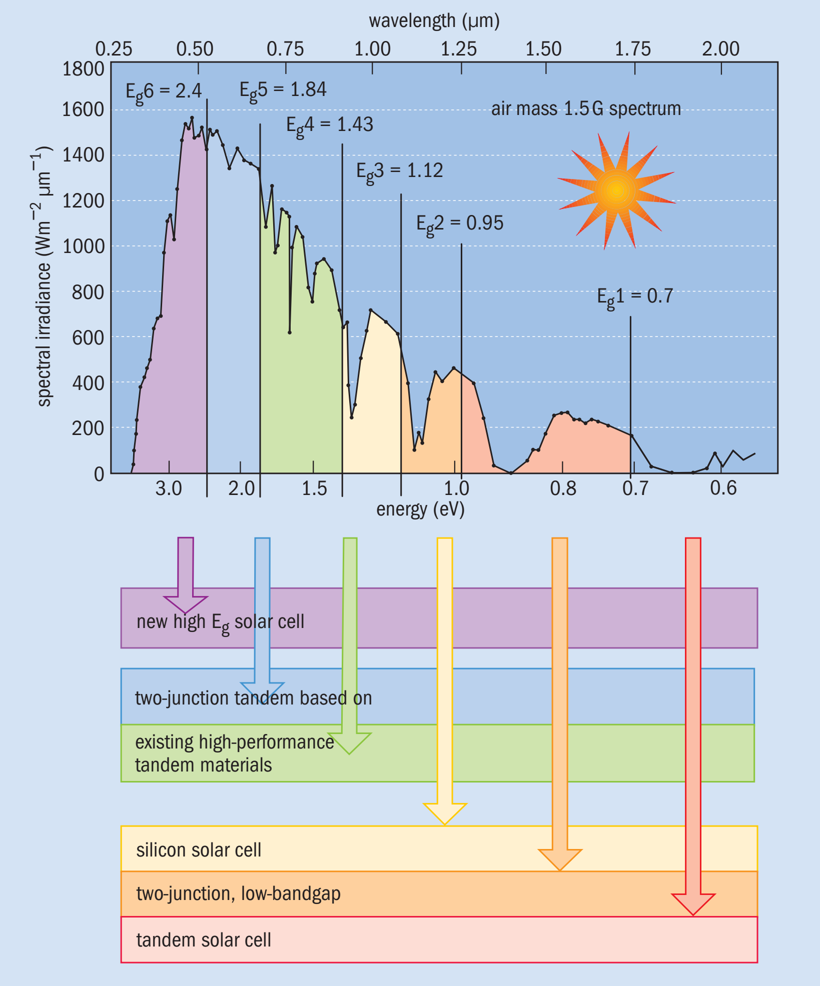
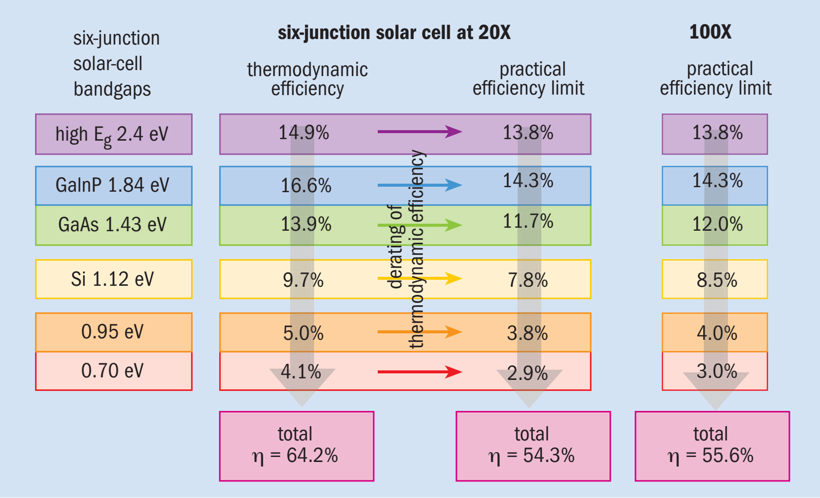


Fig. 3. The consortium plans to build a high-bandgap solar cell, a two-junction tandem cell and a cell made from silicon and low bandgap materials to cater for the high-, medium- and low-energy photons.



six-junction solar-cell bandgaps	six-junction solar cell at 20X		100X
	thermodynamic efficiency	practical efficiency limit	practical efficiency limit
high E_g 2.4 eV	14.9%	13.8%	13.8%
GaInP 1.84 eV	16.6%	14.3%	14.3%
GaAs 1.43 eV	13.9%	11.7%	12.0%
Si 1.12 eV	9.7%	7.8%	8.5%
0.95 eV	5.0%	3.8%	4.0%
0.70 eV	4.1%	2.9%	3.0%
	total η = 64.2%	total η = 54.3%	total η = 55.6%

Fig. 4. A 50% efficiency goal for a six-junction cell can be broken down into targets for each device.

0.95 eV and 0.7 eV that could be made from either III-Vs or germanium-based compounds. The specific bandgaps for these cells, their thermodynamic efficiencies and their practical efficiencies at 20× and 100× concentrations are listed in figure 4. “We’ve built our whole approach on a silicon platform because it is well known, well established and you’re standing on the shoulders of something that’s known to be good,” explained Barnett.

Research has already been carried out for each type of cell. GaInP/GaAs tandem cells for the mid-energy bin have been built with efficiencies of 28.4% and 29% at solar-cell concentrations of 20 and 40 suns, respectively. This is a very encouraging value, says Barnett, because the theoretical maximum for a two-junction cell is only 41.6%. If all three bins had devices offering this performance level, then the DARPA’s target of 50% would be comprehensively broken.

GaInAsP/GaInAs tandem cells are being investigated for the low-energy bin. These MOCVD-grown devices feature 0.95 eV and 0.74 eV subcells on an infrared-transparent iron-doped InP substrate interconnected with an essentially transparent tunnel junction. The back contact is attached to the device mesa and the front contact is made through a highly conductive window layer on the front-side of the device. This solar cell produced an efficiency of 3.5% at a concentration of 5.7 suns and improvements are expected when a two-layer antireflection coating is added and changes are made to allow higher concentration ratios.

Efforts are also being directed at developing InGaN-based cells for the high-energy bin that draw upon advances made in GaN LED and photodetector technologies. PIN structures have been grown by MOCVD on 2 inch sapphire substrates that feature a low-temperature GaN nucleation layer, a 2 µm-thick GaN template and InGaN layers with an indium-concentration ranging from 0 to 40%, which correspond to bandgaps of 3.4 eV to 2.4 eV. Devices ranging from 1 × 1 mm to 5 × 5 mm were fabricated from these wafers. Internal quantum efficiency measurements on these cells, which have an $In_{0.05}Ga_{0.95}N$ absorption layer, show quantum efficiencies of up to 60% at 3.26 eV. Improvements to the cell efficiency can be made by decreasing the light absorption in the current-spreading metal layer and reducing recombination at heterojunction interfaces.

The consortium is also investigating alternative lower-cost growth techniques, such as bio-fabrication processes that can make electronically active material at room temperature and standard pressure. The processes are capable of yields greater than 50% of the starting feedstock, which is at least five times more than typical MOCVD processes. At the University of California, Santa Barbara, Daniel Morse, Birgit Schwenzer and co-workers have used this approach to form GaN and other optoelectronic materials at very low temperatures using ammonolysis – a bio-chemically inspired process route.

The progress made on low-temperature processing techniques, devices for each of the three energy bins, and the dispersive concentrator have been described by Kirkpatrick as phenomenal. “I think we will turn the solar world on its ear over the next 18 months. This architecture gives everybody the freedom to succeed, and I think that’s going to make a big difference.”●