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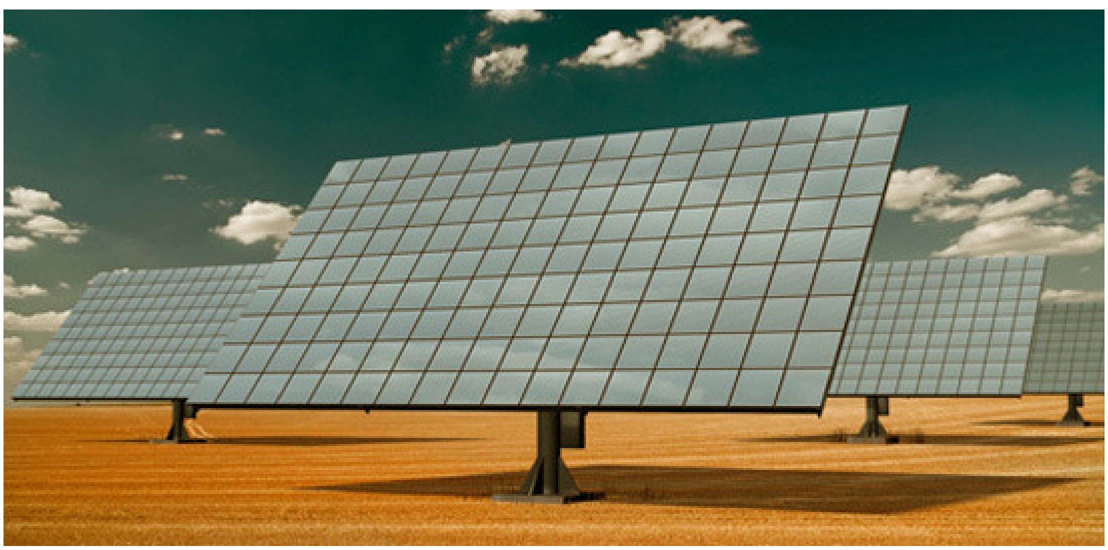
Cheaper by the Dozen: Making Solar Energy Affordable

by Sean Matlis

Historically, economic growth and prosperity have been tied to increased use of energy. Smarter technology may allow us to be more efficient in our energy use, but it's still difficult to envision hundreds of millions of people around the world emerging from poverty without greater use of energy. But where, exactly, will that energy come from? Fossil fuels are and have been our chief energy source, but they pose significant dangers, ranging from those seen in the huge oil leak associated with the Deepwater Horizon disaster in the Gulf of Mexico to the less immediate but potentially graver risks of global warming. And leaving aside environmental considerations, fossil fuels may eventually run out and almost certainly will rise in price as demand grows and readily available reserves are exhausted. [See The Deepwater Horizon Oil Leak, June 2010; Global Warming Report: UN Warms Up to Climate Change, February 2007]

So, are we to swear off oil, coal and the like? It's not so easy. Today there's no true source of clean, cheap energy. Wind, thermal, solar — except in special circumstances, they are at present not economically competitive. But perhaps this situation will change soon.



Semprius

An artist's conception of cost-effective solar panels made with gallium arsenide (GaAs) semiconductors.

A recent advance by a team of scientists at the University of Illinois brings us a step closer to cost-effective electricity from solar cells. The research, led by John A. Rogers of the University of Illinois at Urbana-Champaign and reported in *Nature*, details a process for manufacturing high-quality gallium arsenide (GaAs) much more quickly and cheaply than had been possible. These semiconductors can then be used as the basis for highly efficient solar cells, as well as other electronic devices.

Photovoltaics — All About Cost

In 2008, 80-90% of worldwide energy consumption came from the combustion of fossil fuels, while solar cells or photovoltaics contributed a not-so-impressive 0.04%, according to the BP *Statistical Review of World Energy 2010*. Why? It basically comes down to cost. In the U.S., energy costs about seven cents per kilowatt-hour (kWh). Electricity from solar cells currently costs about 15-20 cents per kWh, though. For the most part, the only way energy production from solar cells can currently compete is through government subsidies. Solar advocates argue that the subsidies make good sense — they will help the industry get established, and as efficiencies are achieved the costs will come down. But there are many programs widely deemed worthy of government funding, and far from enough money to fund them all. To make solar energy a bigger factor in the near term, scientists and engineers need to find a way to make solar cells both less expensive and more productive.

Most solar cells today are made from silicon semiconductors. Silicon is cheap by semiconductor standards, but solar cells made from it are usually only about 20% efficient in capturing energy from sunlight, and manufacturing costs are not low enough for that to be feasible. Gallium arsenide (GaAs) is more efficient in translating sunlight into electricity: Due to a direct band gap and high electron mobility, multi-junction GaAs solar cells can be up to about 40% efficient. Unfortunately, GaAs solar cells are much more expensive to manufacture than silicon ones, so they are still impractical. While less efficient, silicon is abundant while gallium is very rare (hence more expensive); also, silicon is more stable and can be manufactured in much larger sizes than GaAs, cutting manufacturing costs. So far, GaAs chips are used only for specialized purposes, like the solar panels of spacecraft. (The cost of putting stuff into orbit is so great that the difference in price between silicon panels and GaAs is insignificant — you go with whatever is best.)

But if GaAs semiconductors could be manufactured more cheaply, their efficiency advantage would come to the fore. This is where the new research enters the picture.

Cooking Solar Panels (and Other Semiconductors) Step by Step

Semiconductors are basically crystals made from substances like silicon (or GaAs) with specific additional molecules that allow them to conduct electricity in a certain way. Because molecular structure is important for how a semiconductor performs, the crystals must be extremely pure with almost no imperfections. Blemishes, like grain boundaries, seriously affect local electrical properties. This purity is hard to achieve, and requires specialized equipment and conditions.

To make a silicon semiconductor, a seed crystal is dipped into molten silicon. Eventually this turns into a huge cylindrical, single-crystal ingot of pure silicon; the ingot is sliced into razor-thin round discs called wafers, which are then polished to make them as smooth and even as possible. These wafers are a very important part of semiconductor fabrication, because the semiconductor devices are grown on them, but they are not actually used for the device themselves because they are still not quite perfect enough.

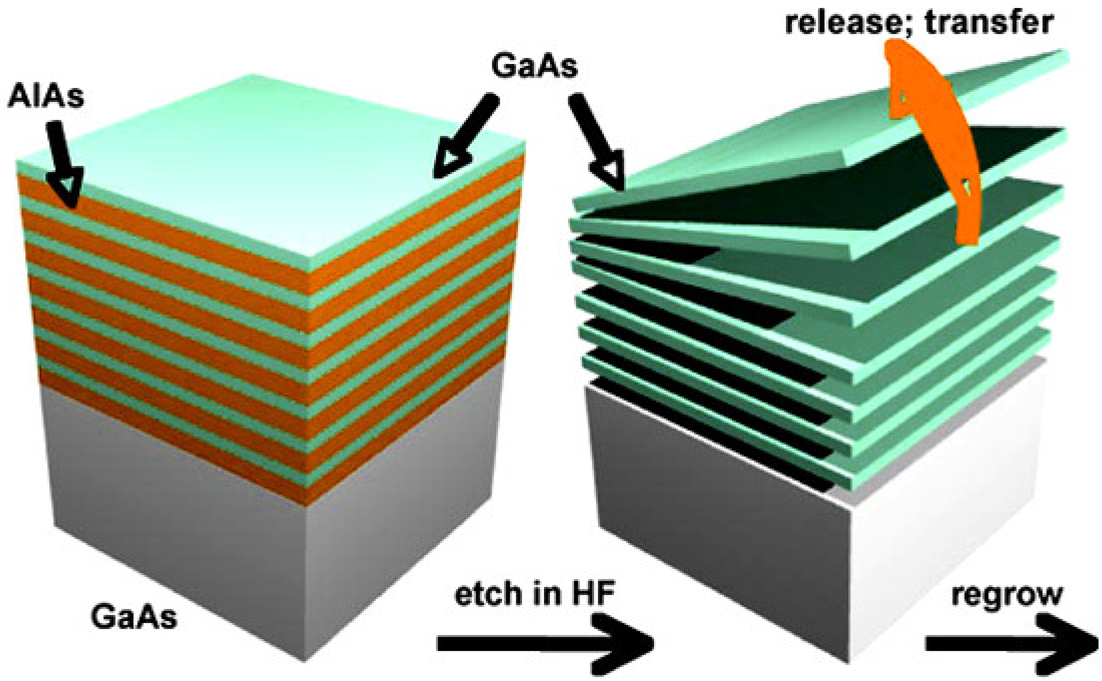
The wafer (silicon in this case) is placed into a clean, vacuum-sealed environment, and a layer of silicon is deposited on top of it, molecule by molecule to make an even more uniform surface. The electronics that are used in chips and solar panels are made from that layer, which has channels cut into it and metal connections laid on top by various techniques. The wafer with the semiconductor device on top may then be chopped up into chips and used in electronics.

You can imagine how wasteful it is to create all these expensive and delicate wafers to grow semiconductors on when they aren't even used as part of the device. This is especially true if a rare material like gallium is used to make them. Suppose every time you wanted to write a note, you had to glue a piece of paper to a clipboard, and then write on it. How bulky and expensive would that be? It would be much easier to attach a pad of paper with many sheets onto the clipboard, tearing off sheets that have been written on to get to a clean sheet below. Then when you get to the bottom of the clipboard, you just put on a new pad of paper instead of making a whole new clipboard.

That's exactly what Rogers and colleagues have done. Rogers observed, "By doing this we can generate much more material more rapidly and more cost effectively. We're creating bulk quantities of material, as opposed to just the thin single-layer manner in which it is typically grown."

The Solar Panel Printing Press

Rogers took a wafer of GaAs and instead of depositing a single layer of GaAs on it, he alternated layers of GaAs and Aluminum Arsenide (AlAs), which has the same molecular structure and can be integrated without causing extra stress. Using the same methods as usual, a device such as a solar cell can be designed and etched into the GaAs layer. But then the AlAs layer can be melted away by exposing it to Hydrofluoric Acid, which doesn't dissolve GaAs. This releases the top layer, just like tearing off the top sheet of paper.



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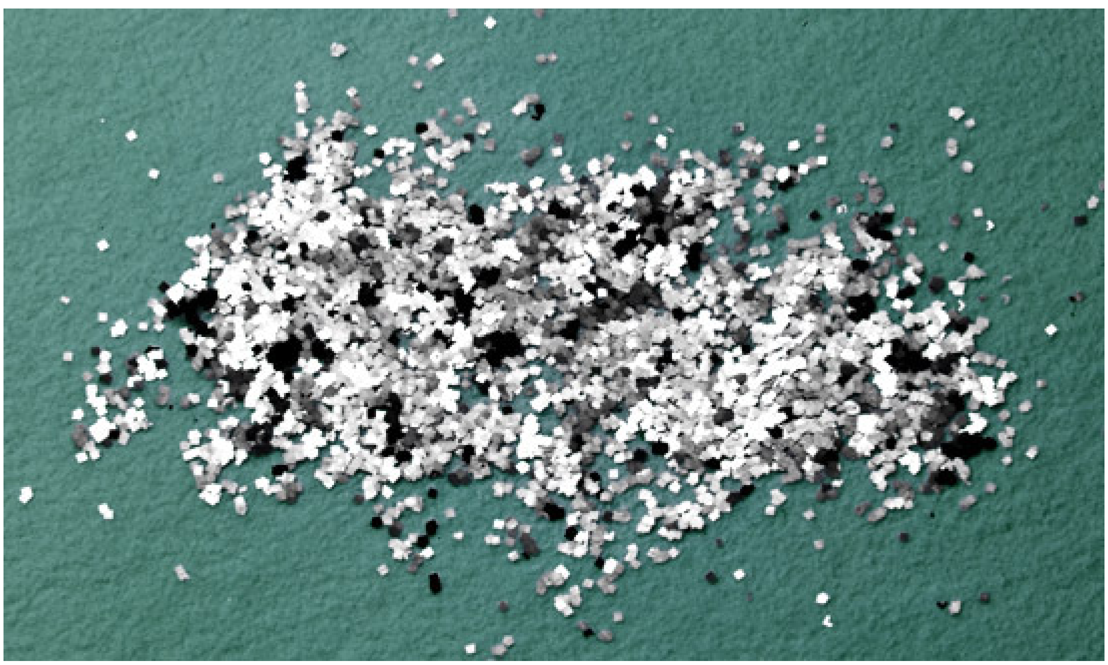
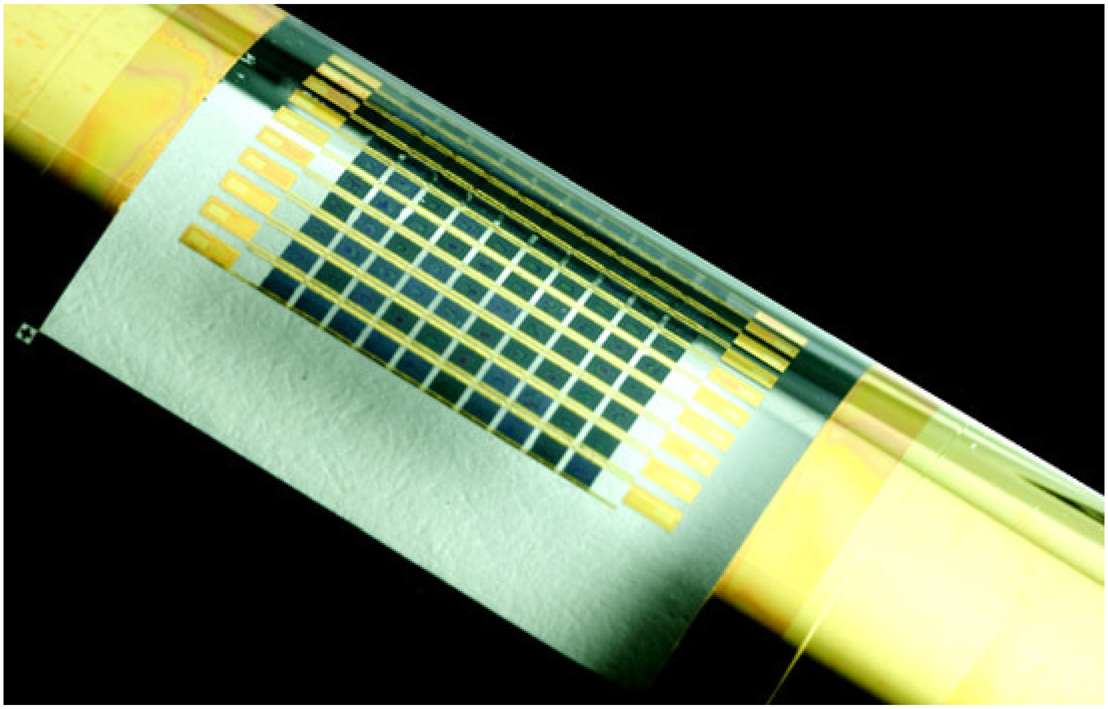
ABOVE: Rogers took a wafer of GaAs and instead of depositing a single layer of GaAs on it, he alternated layers of GaAs and Aluminum Arsenide (AlAs). A solar cell then was designed and etched into the GaAs layer and the AlAs layer was melted away with acid. This released the top layer of GaAs, just like tearing off the top sheet of a paper pad. BELOW: GaAs solar cells manufactured in stacks and then peeled apart.



Courtesy of John A. Rogers

Using a technique that Rogers pioneered several years earlier, a soft elastomeric pad picks up that released top layer, which is too thin and fragile to be handled, and stamps it onto a substrate like glass or plastic or silicon that has been coated with a sticky material. (A substance is elastomeric if it behaves like rubber, and can recover its shape after being deformed.)



Courtesy of John A. Rogers

The GaAs wafer, which is too thin and fragile to be handled, is stamped onto a substrate of plastic that has been coated with a sticky material. ABOVE: A photovoltaic module contains an array of GaAs solar cells on a plastic sheet.

This process has many benefits. The semiconductor can be stamped over a large area, like plastering a bunch of flyers on a wall, so that you can effectively make a huge chip instead of having a bunch of small ones. This allows for the fabrication of a larger solar cell, for example.

"For photovoltaics, you want large area coverage to catch as much sunlight as possible. In an extreme case we might grow enough layers to have 10 times the area of the conventional route," Rogers said in a press release. "You really multiply the area coverage, and by a similar multiplier you reduce the cost, while at the same time eliminating the consumption of the wafer."

The process also allows the wafer to be reused, cutting down quite a bit on time and cost. Instead of accounting for 40% of the manufacturing cost of the solar panel, the wafer accounts for about 4%. Manufacturing time is cut down as well, because in one session you can make up to around 40 layers (at a maximum), instead of starting and stopping the machine 40 times.

"If you grow 10 layers in one growth, you only have to load the wafer one time," said Li, a coauthor on the paper. "If you do this in 10 growths, loading and unloading with temperature ramp-up and ramp-down takes a lot of time. If you consider what is required for each growth — the machine, the preparation, the time, the people — the overhead saving our approach offers is a significant cost reduction."

Moreover, the stamping process allows for a wider range of uses and increased mechanical robustness. Since only a thin layer is stamped down, it's flexible; in principle, it could be used to make a bendable solar cell or chip. The semiconductor devices can also be integrated into a variety of materials, such as glass, plastic, or silicon. Different types of chips can even be made on the same wafer, so some layers could be intended for a solar cell, some for a logic chip, and some for a light sensor.

The Swiss Army Semiconductor Manufacturer

While the process has not yet been optimized for specific devices, the results are promising. Manufacturing costs for GaAs semiconductors were reduced by about 90%. The best reported efficiency for single-junction solar cells is between 20.6% and 25.8%, and Rogers's team has been able to achieve about 20.5%. The lab's partner company, Semprius Inc., located in North Carolina, is beginning to use the technology to make solar cells, and has reported efficiencies for multi-junction solar cells as high as 35-37% (out of a theoretical maximum of about 40%). The stacking and printing technique has also been effective in making chips for light sensors, near infrared imagers, and very fast logic circuits.

The researchers see room for improvement in several ways. One objective will be to increase the size of the manufactured chips. At present they are still very small, ranging from 200 to 2,000 micrometers square; size increases should yield improvements in efficiency. Another possible line of research centers on adapting the process to different types of devices and different semiconductor materials, such as gallium nitride and indium phosphide, which are used for LEDs and laser diodes.

Of course, the big prize is making cheap electricity out of sunlight. The researchers hope their advances will help achieve the Department of Energy's stated goal of producing electricity at $0.05 per kilowatt-hour. If that happens, fossil fuel will finally have a serious competitor.

John A. Rogers: Engineering Efficient Solar Energy

John A. Rogers is the Lee J. Flory Founder Chair and professor of materials science and engineering at the University of Illinois at Urbana-Champaign. Rogers earned his undergraduate degrees in chemistry and physics from the University of Texas at Austin in 1989. He did his graduate studies in physical chemistry at the Massachusetts Institute of Technology (MIT), completing his master's degree in 1992 and his Ph.D. in 1995. For the next two years, Rogers worked as a junior fellow at Harvard University. Prior to joining the University of Illinois faculty in 2002, Rogers did condensed matter physics research at Bell Laboratories. He has received numerous awards and honors, holds more than 70 patents, cofounded several companies, and has published over 250 peer-reviewed papers.

Rogers research focuses on "fundamental and applied aspects of nano and molecular scale fabrication as well as materials and patterning techniques for unusual format electronic and photonic systems." His research group "seeks to understand and exploit interesting characteristics of 'soft' materials . . . as well as hybrid combinations with unusual classes of micro/nanomaterials . . ." Rogers currently is concerned with "soft materials for flexible macroelectronic circuits, nanophotonic structures, microfluidic devices, and microelectromechanical systems."

Below are Rogers's June 28, 2010 responses to questions posed to him by Today's Science.

Courtesy of John A. Rogers/UIUC

"We believe that photovoltaics will be a very important part of the energy mix in the future. Right now, cost is the main barrier. We're optimistic that technology advances will eliminate this shortcoming."

Q. When did you realize you wanted to become a scientist?

A. Very early, in elementary school, stimulated by a science fair competition. My father, who has a Ph.D. in physics, was a big influence.

Q. How did you choose your field?

A. My field is materials science and engineering. This area is appealing because (1) materials are central to every area of engineering, and (2) the work involves both issues of fundamental scientific interest and aspects of device engineering.

Q. Are there particular scientists, whether you know them in person or not, that you find inspiring?

A. Prof. George Whitesides, my postdoctoral advisor from Harvard, is one of my role models. His ability to do both science and engineering, at the highest levels, is unmatched.

Q. When you tell people that you are a materials scientist interested in nano and molecular scale fabrication, what is their reaction? What do you think is the biggest misconception about your profession?

A. Typically, people are very interested and enthusiastic. In rare cases, misperceptions about the safety of nanotechnology can cause some concern.

Q. Would the approach you describe in your study work (with perhaps some modifications) for other materials besides gallium arsenide?

A. We think that it will be applicable to many types of compound semiconductors, including perhaps GaN [gallium nitride](of interest for applications in solid state lighting, and other areas).

Q. Do you think photovoltaic cells will become a major factor in world electric supply? What key barriers must still be overcome?

A. We believe that photovoltaics will be a very important part of the energy mix in the future. Right now, cost is the main barrier. We're optimistic that technology advances will eliminate this shortcoming.

Q. Do you think one kind of solar cell will become dominant, or that there will be a patchwork or different varieties filling different niche needs?

A. Probably a variety. GaAs, for instance, work economically only in a mode that involves focusing lenses and mechanical trackers that can follow the sun. These systems are useful for utility scale power generation, but might not be suitable for home installations (where Si, for example, is appealing).

Q. Where do you spend most of your workday? Who are the people you work with?

A. In the office, in the lab and at scientific conferences. I work closely with the students and postdoctoral fellows in my group, and with collaborating professors here at Illinois and other universities. We also have several startup companies that are commercializing technologies out of the group. The company Semprius is pursuing the technology described in the May *Nature* paper. In fact, two former Ph.D. students who are now full-time employees at Semprius are co-authors.

Q. What do you find most rewarding about your job? What do you find most challenging about your job?

A. The most rewarding aspects are in teaching students, and developing technologies with societal benefit. The most challenging aspect is in the uncertainty of the discovery process — sometimes things do not work as expected.

Q. What has been the most exciting development in your field in the last 20 years? What do you think will be the most exciting development in your field in the next 20 years?

A. The discovery and application of semiconducting nanostructures and materials represent two extremely exciting developments. The ability to engineer electronic properties through size and shape is very general, and very powerful. The next 20 years will see the use of these materials in devices with wide-ranging applications, from systems for low-cost production of energy to components for diagnosing and treating disease.

Q. How does the research in your field affect our daily lives?

A. We are presently working on next-generation photovoltaics and on a field that we are calling 'bio-integrated' electronics. Successful efforts will have obvious, diverse impacts on daily life.

Q. For young people interested in pursuing a career in science, what are some helpful things to do in school? What are some helpful things to do outside of school?

A. Focus on school, and do well in your coursework. Try to use your summers to get some experience in academic and industrial life, through internship programs. Most of all, look for topics that are exciting and fun, with some potential for practical benefit. Pursue those things.

Discussion Questions

What are some other technological improvements that have centered on increasing efficiency of production? How might flexible solar cells or computer chips be used?

Journal Abstracts and Articles

(Researchers' own descriptions of their work, summary or full-text, on scientific journal websites).

"GaAs Photovoltaics and Optoelectronics Using Releasable Multilayer Epitaxial Assemblies." www.nature.com/ nature/ journal/ v465/ n7296/ abs/ nature09054.html.

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