



LEVERAGING SEMICONDUCTOR SCIENCE **FOR CLEAN ENERGY TECHNOLOGIES**

Keeping the lights on in the United States consumes 350 billion kilowatt hours of electricity annually. Most of that light still comes from incandescent bulbs, which haven't changed much since Thomas Edison invented them 140 years ago. But now a dramatically more efficient lighting technology is seeing rapid adoption: semiconductor devices known as light-emitting diodes (LEDs) use 85 percent less energy than incandescent bulbs, last 25 times as long, and have the potential to save U.S. consumers a huge portion of the electricity now used for lighting.

High-performance solar power plant in Alamosa, Colorado. It generates electricity with multi-layer solar cells, developed by the National Renewable Energy Laboratory, that absorb and utilize more of the sun's energy.
(Dennis Schroeder / National Renewable Energy Laboratory)

How we generate electricity is also changing. The costs of solar cells that convert light from the sun into electricity have come down dramatically over the past decade. As a result, solar power installations have grown rapidly, and in 2016 accounted for a significant share of all the new electrical generating capacity installed in the U.S. This grid-scale power market is dominated by silicon solar cells, using manufacturing techniques pioneered by the electronics industry for making computer chips. In addition, new markets are emerging for solar cells with much higher efficiencies—more complex cells based on advanced semiconductor science that require novel production methods. Such cells may soon power the growing number of sensors and other smart devices in cars, consumer products, and buildings.

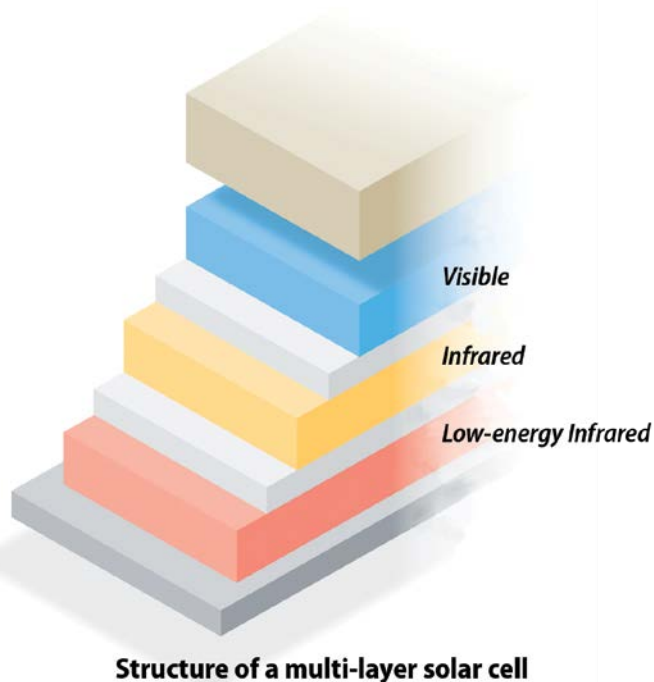
These energy-saving or generating techniques all have roots in the semiconductor technology that spawned the IT revolution. But they required years of additional fundamental and applied research to enable commercial technologies.

Solar cells are semiconductor devices that, when they absorb sunlight, generate electrons that can be collected

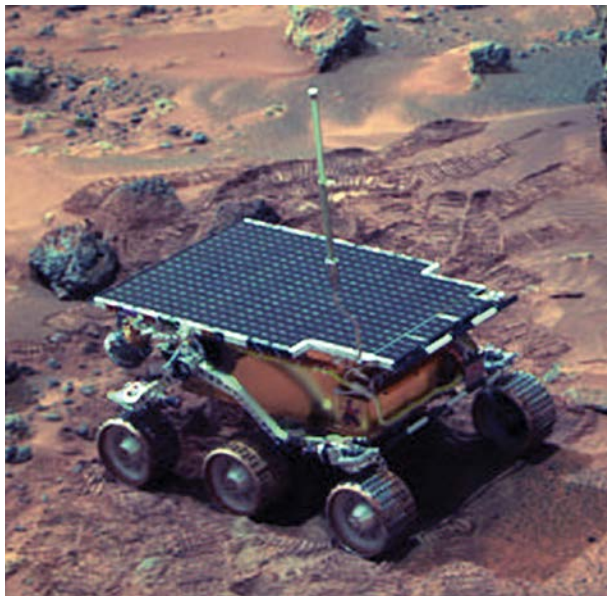
to produce an electrical current. The challenge has been to improve the efficiency with which solar cells convert sunlight to electricity and to reduce their cost for commercial applications. Initially, solar cell production techniques borrowed heavily from the semiconductor industry. Silicon solar cells are built on wafers cut from ingots of crystal-line silicon, just as are the chips that drive computers. Production costs have dropped dramatically—which is why silicon solar cells continue to dominate the industry. However, several decades of basic and applied research supported by DOE's Basic Energy Sciences (BES) office and other DOE programs has led to several new families of more efficient solar cells. Some, such as the cadmium telluride cells manufactured by First Solar, are already commercial products.

Of particular interest for the emerging new high efficiency solar cell markets, however, are multi-layer cells that combine two, three, or more thin layers, each of a different semiconductor material. These exploit the fact that sunlight spans a range of wavelengths—from high energy ultraviolet through visible wavelengths to lower energy infrared—and any one material absorbs and converts only a portion of those wavelengths. A multi-layer cell composed of the right combination of materials can capture far more energy—and indeed, some have shown efficiencies close to 45 percent (as compared to silicon at 25 percent, both under laboratory conditions). High-efficiency cells have long been deployed to power satellites and spacecraft, including the Mars Rover. But creating such cells for wide-spread use on the ground involves unique complexity: combining materials with different electronic and structural properties is not easy; manufacturing them is harder still.

The research on multi-layer cells began in the early days of the National Renewable Energy Laboratory (NREL). BES supported theoretical work and advanced instrumentation needed to characterize the semiconductor materials. The Energy Efficiency and Renewable Energy (EERE) office supported more applied work aimed at actually building multi-layer cells. But the NREL staff was small at that time, and both sets of researchers shared the same coffee machine, so a unique collaboration was born. That collaboration enabled the researchers first to understand and eventually to control the properties of a compound semiconductor material called *gallium indium phosphide*, and then to combine it with *gallium arsenide*—resulting in the first multi-layer cell.



The three active semiconductor layers of this solar cell absorb sunlight from different parts of the solar spectrum—visible (blue layer), infrared (yellow layer), and lower-energy infrared (pink layer)—enabling higher overall efficiency. (National Renewable Energy Laboratory)



High-efficiency multilayer solar cells have been extensively used to power satellites and space vehicles, such as the NASA Mars Rover vehicle shown here.

(National Renewable Energy Laboratory)

That collaboration—side-by-side work on both basic and applied problems—has continued for more than two decades, yielding significant progress. Likely candidate cells for commercialization now contain four layers, and are getting close to the goal of 50 percent efficiency, while new approaches to manufacturing such complex products are emerging that could significantly lower costs. Moreover, new potential applications have emerged that are less cost-sensitive than grid-based power and that come with powerful technical partners.

The semiconductor production problem facing multi-layer solar cells turns out to be essentially the same as that for making the laser-based radar chips needed for self-driving cars. There are now both large companies and several startups focused on that problem, building on the work done at NREL. Moreover, both Apple and Google want to power their smart watches with these very high-efficiency cells, and have assigned hundreds of engineers to the task. Waiting in the wings are applications for the millions of smart sensors associated with the Internet of Things that will need to be powered not by batteries but by sunlight or even the ambient light within buildings. The pay-off for the decades of patient research—twinning basic and applied work—looks promising indeed.

LEDs essentially reverse the solar cell process. When a voltage is applied across an LED, electrons from one side of the semiconductor device and holes (missing electrons) from the other side combine to release energy in the form of light. LEDs have no filaments to burn out, unlike incandescent lights, and produce far less heat—which accounts for their long lifetimes and high efficiencies. LEDs are now found in many kinds of devices: they form the numbers on digital clocks, indicate when appliances are turned on, and collected together can illuminate traffic lights or form images on a TV screen.

For conventional lighting, however, white light is needed. An important breakthrough that transformed LED research occurred in the late 1980s when Japanese scientists made the first devices that emitted blue light, using another compound semiconductor material, *indium gallium nitride*, also far more complex than silicon. Blue light is critical, because it can be converted into red, yellow, and green light by passing it through wavelength converters—and then combined to form white light. The potential for semiconductor-based—or solid state—lighting was recognized but not widely accepted by industry until much later, although the discovery did set off an explosion of research. The challenge was to understand how these novel LEDs worked, to improve their design, and to perfect the complex method by which they are manufactured—a method that involves depositing a thin layer of the compound materials on a supporting substance while precisely controlling its chemistry.

Over the following several decades, while DOE's EERE office supported applied work, several types of BES-supported basic research were critical:

- > First, the science underlying the deposition process to make it accurate enough to produce a reliable product;
- > Second, work on the underlying mechanisms that enable efficient light emission, despite the presence of defects and other complicating factors;
- > Third, on-going work to incorporate a new nanotechnology called quantum dots into solid state lighting to replace the wavelength converters, increasing the overall efficiency still further and enabling more precise control of colors.



Semiconductor devices known as light-emitting diodes are not only very efficient, but can also be “tuned” to emit light of different colors for different purposes—“warm” white light for human residential use, or “cooler” white light that helps plants grow optimally for indoor agricultural use. (*Zhang Sheng / Shutterstock.com*)

As a result, scientists working in universities, national laboratories, and industry have been able to tailor the semiconductor materials used to make LEDs in ways that enable them to produce light of different colors, more efficiently, and eventually with the high-intensity light needed for many commercial applications. New light-emitting materials, such as organic LEDs, have also been developed that show promise for the future.

Together these efforts along with more applied research helped catalyze the emergence of a strong U.S. solid state lighting industry. Indeed, over the last decade, DOE has supported over 200 research projects on solid state lighting including LEDs, which in turn have led to more than 270 patents awarded or applied for and a large and growing new industry with countless numbers of new high-efficiency lighting products.

The advantages of solid state lighting are many. LEDs are far more efficient—the best commercial devices now

convert electricity into light with an efficiency 10 times greater than a traditional incandescent bulb (15 times greater for advanced LEDs still under development). Because of their long lifetimes, LED lights are also more cost-efficient. They can also be “tuned” electronically to modify the color or intensity of the light for specific applications—a warm light for human use, a harsher light for outdoor security applications, still other characteristics to optimize plant growth for indoor agriculture. Even though market penetration is still in the early stages, U.S. energy savings from solid state lighting in 2016 amounted to more than one-third of the electricity previously used for lighting. Adoption of solid state lighting is now so rapid that it is expected to dominate the lighting industry within another decade, marking one of the fastest technology shifts in history. Estimates are that this semiconductor technology will save U.S. electricity consumers as much as 85 percent of their lighting bill by 2035.