Insect Eyes Inspire Improved Solar Cells

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Taking a cue from nature, these researchers looked to the compound eyes of insects as a model for developing their unique approach to harvesting sunlight.

Have you ever tried to catch a housefly? Unless you have the agility of Bruce Lee or the air is cold and damp, you have probably been unsuccessful. Both the placement and the structure of the two eyes of a housefly—as well as of insects of many other species—are such that they provide the insect with a wide angular field of view, far more than that of humans.

The fly can see your hand approaching from behind it, and it can usually take swift evasive action. Its wide angular field of view inspired us to conceive and examine structures to improve the efficiency of solar cells in converting sunlight into electric current. This is a scientific topic of abundant societal value today. Never before have we faced such a strong global demand for non-polluting sources of plentiful energy.

A short history of solar power

Capturing solar energy is not a new idea. Some ancient authors report that, more than two millennia ago, in 212 B.C.E., during the siege of Syracuse (Sicily) by the Roman fleet, the famous scientist Archimedes used a machine capable of setting fire to the enemy ships. It's not clear whether this story is legend or fact, but if it happened, the engine most likely consisted of an array of highly polished bronze or copper shields acting as mirrors; they would have been placed in a manner to focus solar energy onto a very small region on an enemy ship in order to ignite the wood that the ship was made of.

Archimedes' use of burning mirrors examplifies how solar energy can be exploited for thermal generation. That idea has been recently resurrected in solar–thermal power plants. There, many

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parabolic mirrors concentrate sunlight onto a receiver where a working fluid is heated and then used in steam turbines to generate electrical energy.

Modern physics allows another way for harvesting and using the energy of the sun—the photovoltaic effect. This effect allows the solar energy to be directly converted into electrical energy. Its discovery dates back to 1839, when a French experimental physicist, Alexandre-Edmond Becquerel, only 19 years old at the time, was performing experiments with an electrolytic cell composed of two metal electrodes. He observed that exposing certain materials (later called semiconductors) to sunlight could generate a weak electrical current.

During the second half of the 20th century, technology evolved for the photovoltaic effect to be used for the large-scale production of electrical energy. Photovoltaic technology requires very little infrastructure for deployment and is thus practical for both small and large installations, such as those on the roofs of homes and commercial buildings. So it's no wonder that modules comprising solar cells dot many landscapes, on the domestic scale as well as the industrial. Along with solar-thermal plants, photovoltaic plants could substantially satisfy the continuously increasing demand for energy with minimal environmental impact.

A photovoltaic power plant is a collection of solar modules whose basic component is the solar cell. Silicon is the most economically viable semiconductor material to make solar cells for terrestrial use, in large part because of the scalable manufacturing technology developed by the electronics industry during the past 50 years. Solar cells made of gallium arsenide are used for solar cells in spacecraft. Still other materials—including multilayered semiconductors, organic materials and polymers—are also being devised, fabricated and tested for future deployment.

Photovoltaics today

The wavelengths in the solar spectrum range from 250 to 3,000 nm, with peak intensity at about 550 nm. For exploiting the photovoltaic effect using silicon, the 400 to 1,100 nm wavelength range must be considered. Despite the evolution of silicon photovoltaic technology for more than half a century, the efficiency of silicon solar cells remains rather low.

Cost remains a big barrier to the widespread adoption of photovoltaic technology, but sunlight is attractive for its limitless potential to provide sustainable (and free) energy. For these reasons, both designing solar cells that are able to harvest as much sunlight as possible and increasing the efficiency of the silicon solar cells are problems that are currently challenging the scientific community.

The harvesting of sunlight can be improved by equipping a solar module with a mechanical system to track the sun so that sunlight always falls perpendicularly on the exposed faces of the cells in the module. As the orientation of the sun changes diurnally as well as annually, the solar tracking system allows frontal exposure of solar cells at all times during the day—just like a sunflower!

However, tracking increases the initial as well as the operational costs and can also malfunction mechanically. Moreover, mounting a solar tracking system on top of a building is typically not easy. As a consequence, solar tracking systems are used almost exclusively in industrial photovoltaic power plants.

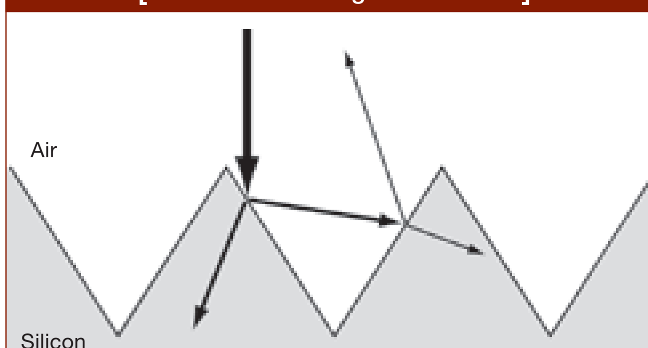
Optimally effective and economical solutions for coupling sunlight into solar cells are needed for small-scale installations—for instance, on and in houses and office buildings. Furthermore, not only should solar cells be designed to harvest energy from direct exposure to sunlight, but a significant fraction should be designed to recycle energy that is put out by other lighting sources.

For instance, when a lamp that is incandescent, compact fluorescent or even LED-based is used in a room, a significant fraction of the light is wasted because it illuminates objects or parts of the room that do not need to be illuminated. Light should be harvested not only from those areas but also from those where illumination is needed after ensuring that the purpose of having indoor lighting is not compromised. Similarly, all of the energy put out as street lighting is not used for the intended purpose.

Therefore, light from engineered sources could also be harvested and recycled, but that requires the use of "solar cells" that can harvest energy from diffuse light. For these reasons, solar cells should have the largest angular field of view (i.e., the angular extent of the directions "seen" by the cell) in order to maximize the capture of the incident light, regardless of its direction.

A large angular field of view would permit the elimination of solar tracking systems as well. In order to increase the efficiency of solar cells, the large angular field of view should be associated with little or no reflection of light at the exposed surface of the silicon solar cell. Thus, it is necessary to reduce the reflection of solar radiation at the air-silicon interface.

[Transmission of light into silicon]



Transmission of light into silicon can be enhanced by texturing the exposed surface of silicon to trap the light rays by multiple reflections.

Nature suggests useful strategies for highly efficient solar cells since natural selection has, over eons, resulted in species endowed with biological structures that allow the capture of light from a large range of directions.

Usually this goal can be accomplished by coating the exposed surface with an antireflection coating made of one or two very thin layers of materials with optical properties between those of air and silicon.

Alternatively, the exposed surface can be textured in order to trap the light rays by multiple reflections. The textures commonly used include regular inverted pyramids, bowls, grooves, honeycombs and other more complicated shapes. However, texturing does not eliminate the need for a mechanical tracking system to effectively enlarge the angular field of view.

Engineered biomimicry

Recently, our international team of researchers—with members from the United States, Italy and Spain—has begun to apply an approach called engineered biomimicry. Underlying this approach is the idea that we can draw from nature when designing new structures and devices. Bioinspiration, biomimetics and bioreplication are progressions in engineered biomimicry.

The goal in bioinspiration is to reproduce a biological function but not necessarily a biological structure. An example is the development of airplanes and helicopters that were inspired by birds and insects in self-powered flight: Neither airplanes nor helicopters have components that resemble significant parts of the anatomies of birds or insects.

Biomimetics involves replicating the functionality of a biological structure by approximately reproducing an essential feature of the structure. A wonderful example is the hook-and-loop structure of Velcro coming from the hooked barbs on a burdock seed. When an animal brushes against the seed, the hooks attach into the fur of the animal, and the seed is carried along until it is either pulled off or drops out of the fur.

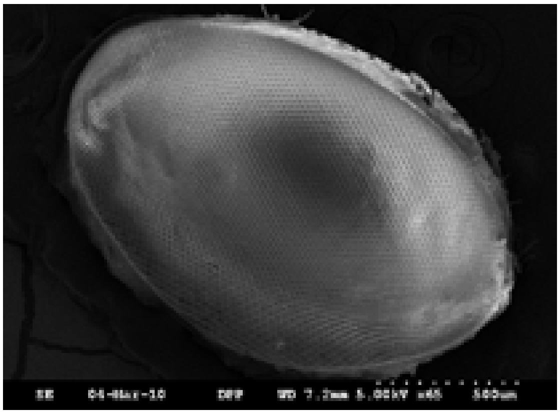
Bioreplication refers to the direct replication of a structure found in natural organisms. Here, the goal is to copy one or more functionalities, with the possibility of providing the bioreplicas with additional functionalities given by the material of choice (phosphorescence, for instance).

Indeed, nature suggests useful strategies for highly efficient solar cells since natural selection has, over eons, resulted in species endowed with biological structures that allow the capture of light from a large range of directions. Houseflies (*Musca domestica*) have big eyes and they can see 270 degrees around them in the horizontal plane. Certainly, this wide angular field of view arises from the positions of the two eyes; humans too would have a much wider angular field of view than what they have (170 degrees) if their eyes were located on their temples. We reasoned that the wide angular field of view could also arise from the compound structure of the eyes of houseflies.

Each compound eye comprises several cylindrical eyelets called ommatidia that are arrayed on a curved surface. Light propagating along the axis of an ommatidium is collected to form an image, but light propagating in other directions and reaching an ommatidium is absorbed by its dark side wall. The compound eye is a macroscale object with linear dimensions of a millimeter or larger. The cross-sectional diameter of an ommatidium is roughly 20 µm. Although the spatial resolution of the overall image formed in the brain by the fusion of the individual images is quite low, the field of view is very large. Other insects such as the common North American blowfly *Eucalliphora lilea* and the South African horsefly *Tabanus sulcifrons* also have compound eyes.

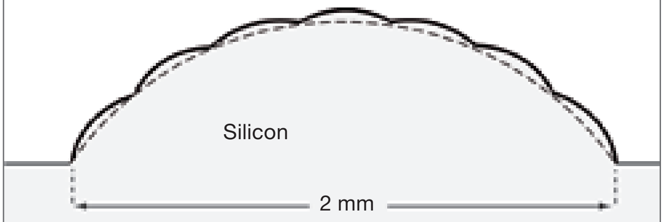
Solar cells are nonimaging optical devices, but they must have as large an angular field of view as possible in order to

[The compound eye of a common blowfly]



The compound eye of a common blowfly (*E. lillea*) comprises several cylindrical ommatidia arrayed on a curved surface.

[Cross section of the silicon surface]



Cross section of the prismatic two-dimensional bioinspired texturing of the silicon surface.

The use of an actual compound eye in the production process itself—i.e., bioreplication—appeared promising to us. Nanocasting methods, which are analogous to the ones used in a steel foundry but on a much smaller length scale, work very well.

maximally harvest the incident light. Therefore, about two years ago, we embarked on a two-phase research program to adapt the scalloped and curved outer surface of a compound eye to texture the exposed face of a solar-cell device. Progress has occurred in both phases, which are being pursued simultaneously.

The first phase requires the numerical simulation of light interacting with the air-silicon interface. A simplified two-dimensional bioinspired texturing of the exposed face was considered as the first step of this phase. The exposed face was supposed to be textured as an array of parallel prisms whose length is tens of thousand times the largest wavelength (1,100 nm) of sunlight in consideration for silicon solar cells. Above the base plane, the cross section of each prism is the arc of a circle (defined as 0^{th}-order texturing), which is decorated further by arcs of smaller circles (1^{st}-order texturing).

Higher-order texturing that consists of "decorating the decorations" was also considered. Computer simulations—of the reflected light as a fraction of the incident light in the maximal angular field of view—allowed the optimal cross-sectional shape of the prisms to be determined and demonstrated. These simulations revealed that the performance of 1^{st}-order texturing cannot be bettered by increasing the texturing order. This sheds some light on why compound eyes in nature did not evolve beyond the first stage of compounding.

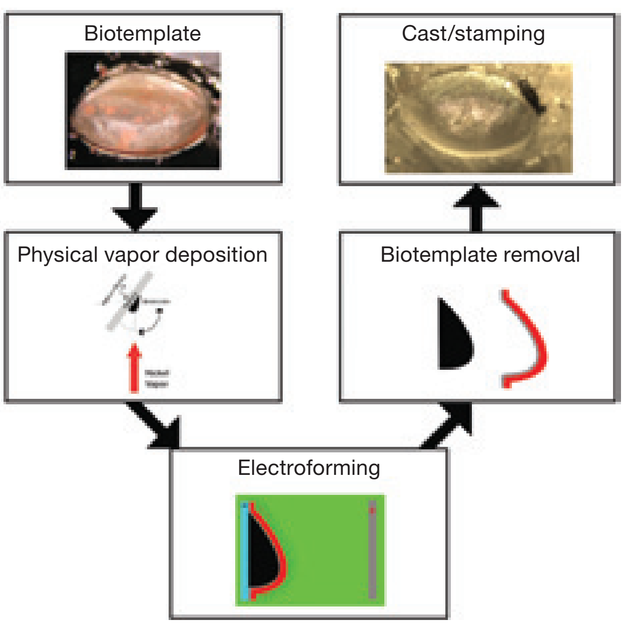
Simulations showed that the best performance was obtained when both the 0^{th}- and 1^{st}-order circular arcs are almost semicircular. For example, if the 0^{th}-order circular arc has a diameter of 2 mm, a good trade-off between performance and complexity of the textured surface is reached when the 1st-order texturing comprises 50 circular arcs of 63 μm diameter.

Results indicated that the bioinspired textured solar cell exhibits light-coupling efficiency—i.e., the solar light transmitted into silicon with respect to the total amount of light impinging on the exposed surface, averaged over the maximal angular field of view and the solar spectrum—that is significantly superior to the commonly used textured and untextured silicon solar cells. This efficiency is comparable to that of antireflection-(AR)-coated untextured silicon solar cells.

In order to improve performance further, the bioinspired prismatically textured surface can be coated with an AR coating. Then the light-coupling efficiency can be enhanced by as much as 93 percent with respect to that of the bare untextured silicon surface, by about 35 percent with respect to the AR-coated untextured surface, and by about 60 percent with respect to the groove-textured surface.

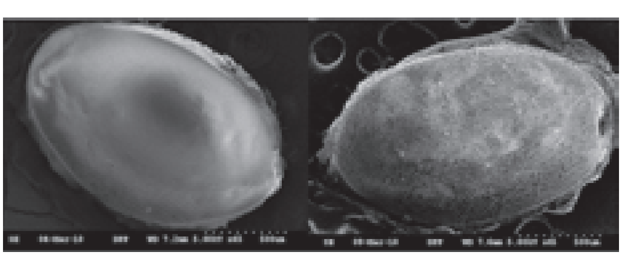
Thus, the first step of this first research phase has led us to conclude that a properly designed and coated bioinspired textured surface can significantly improve the light-harvesting capabilities of silicon solar cells. The substantial enhancement of light-coupling efficiency could more than justify the additional expense of texturing and coating. Furthermore, bioinspired texturing can be implemented on polymer sheets that could be glued on to flat solar cells, whether made of silicon or some other semiconductor.

[The Nano4 technique]



In four steps, the Nano4 technique yields multiple replicas of a single compound eye.

[Cornea of a blowfly and a Nano4 replica]



Images of (left) the cornea of a blowfly and (right) a polymer replica of a cornea produced with the Nano4 technique. These images were produced with a magnification of 65X on a scanning electron microscope.

The second phase of our research program involves the replication of the surface of the corneal layer of a compound eye. The characteristic lengths of the morphology of the eye range from about 200 nm to a few mm. Direct fabrication of such a structure—e.g., by first reverse-engineering the structure and then using a beam of ions to either carve a work piece (top-down approach) or deposit the structure (bottom-up approach)—will be tedious. It will require sophisticated equipment and be very expensive.

The use of an actual compound eye in the production process itself—i.e., bioreplication—appeared promising to us. Nanocasting methods, which are analogous to the ones used in a steel foundry but on a much smaller length scale, work very well. But these methods can produce just one replica per biotemplate (i.e., the compound eye) and are therefore unsuitable for the production of a large number of bioreplicas from a few biotemplates. Other bioreplication techniques such as imprinting and atomic layer deposition also have the same deficiency.

We have devised and partially implemented a four-step hybrid nanomanufacturing technique—dubbed the Nano4 technique—to manufacture multiple high-fidelity replicas of a single biotemplate. In the first step, we directed a collimated vapor of nickel towards the biotemplate mounted on a rapidly rotating and rocking platform in a high vacuum. Within a few minutes, a 250-nm-thick conformal coating is deposited on the biotemplate. In the second step, a roughly 60-μm-thick structural layer of nickel is electroformed onto the thin layer to give it the structural integrity needed for casting or stamping.

The biotemplate is then plucked off and plasma ashing is carried out to completely remove all organic material. What is left behind is a master negative made of nickel. This can be used either as a die for stamping or a mold for casting multiple replicas. We have implemented only casting as the fourth step of the Nano4 technique, with fidelity at the 2-μm scale; stamping is expected to improve the reproduction fidelity at even lower length scales. The technique can produce multiple replicas simultaneously of multiple biotemplates.

Thus, in our quest to significantly improve the performances of solar cells, we have taken both the bioinspiration and the bioreplication routes. Although our simulations in bioinspiration have been restricted to quasi-two-dimensional texturing of silicon solar cells, we are currently extending the simulations to three-dimensional texturing that will mimic the compound eyes of insects realistically. We also need to explore similar texturing of solar cells made of other semiconductors and polymers. The bioreplication approach we have taken is very suitable for flexible solar cells made of soft materials, and it appears to be adaptable for the hard surface of silicon. We are confident that the best is yet to come.

[3x3 array of blowfly corneas]

Optical image of the underside of a 3 x 3 array of blowfly corneas after coating, electroforming and removing some of the corneas. In this photograph, the corneas have been removed from the upper two rows to reveal the negative, but they have been left in place in the bottom row.

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