QUANTUM DOT SOLAR CELLS

The best of both worlds

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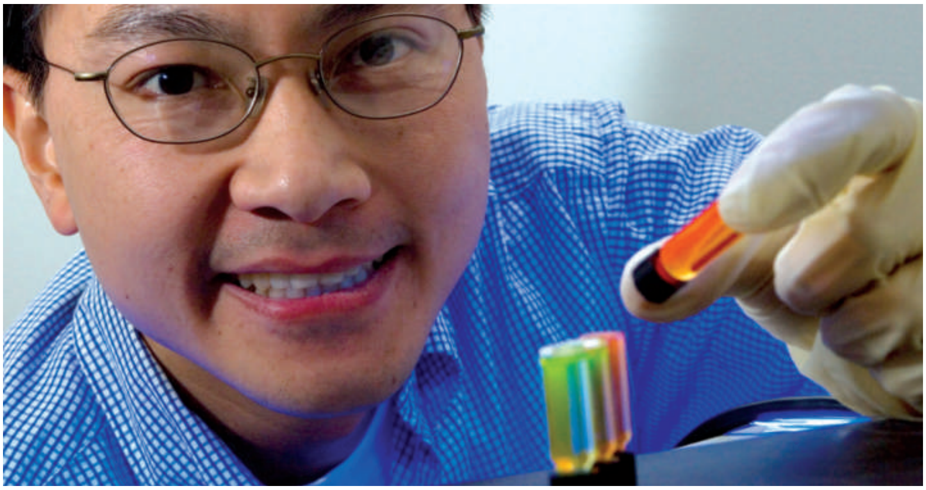
Quantum-dot-based solar cells promise to deliver efficiencies approaching those of crystalline solar cells but with the manufacturing simplicity of organics.

Crystalline materials such as silicon, cadmium telluride and copper indium gallium diselenide (CIGS) currently dominate the solar-cell market, with organic and dye-sensitized devices being regarded as the emerging technologies. However, large areas of crystalline solar cells are inherently difficult and expensive to manufacture, and organic technologies have so far been unable to compete in terms of power-generation efficiency.

Fortunately, there is another technology on the horizon that promises to deliver the best of both worlds — the ease-of-manufacturing of organic solar cells, combined with efficiencies approaching those of crystalline technologies. After many years of research and the development of a cost-effective production technique, quantum dot solar cells based on semiconductor nanocrystals embedded in an appropriate medium are now becoming a commercial reality.



RICE UNIVERSITY

The size tunability of quantum dots enables photovoltaic devices to harvest a broad range of wavelengths over the solar spectrum. Here, various phials containing quantum dots of different sizes (in solution) can be seen. The different colours indicate different absorption bands of light.

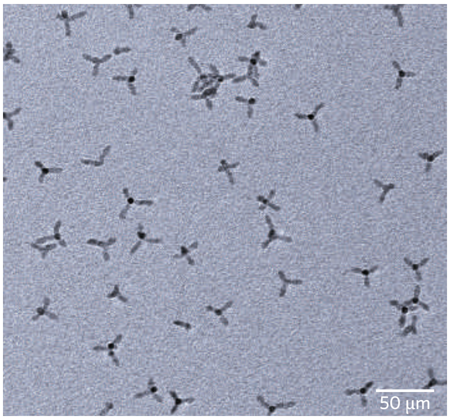
Until now, the most limiting factor in the development of commercial quantum dot solar cells has been their cost. The historically high prices for the quantum dot feedstock have meant that a cell could not be fabricated at a cost low enough to compete with conventional silicon solar cells, let alone with fossil fuel energy sources. However, the capacity to now produce industrial amounts of quantum dots is finally making it possible to fabricate high volumes of quantum dot solar cells at competitive prices.

Advances in chemistry and nanotechnology have also made it possible to manufacture quantum dots from different types of semiconductor nanocrystals easily and uniformly, avoiding the need for a clean room, a high-temperature process and ultrahigh-vacuum equipment.

To appreciate the attraction and potential of quantum dot solar cells, it is first necessary to understand the limitations of existing photovoltaic technology. Conventional silicon solar cells do not absorb the entire spectrum of the sun's energy. Electron–hole pairs are generated when photons with energies more than the bandgap of silicon (1.1 eV ~ 1.1 μm) are absorbed, with electrons being excited to the conduction band and holes being created in the valence band. However, a significant part of solar radiation is composed of visible- and ultraviolet-wavelength photons, which have energies far exceeding the bandgap of silicon. Such energetic, shorter wavelength photons excite electrons into higher levels of the conduction band. These 'hot' electrons then relax to the bottom of the conduction band (the associated holes relax to the top of the valence band) by giving up phonons, thus heating up the silicon crystal but not bringing any useful benefit for electricity generation. Such heating can also degrade the performance of the cell.

These problems can all be solved using quantum dot technology. The bandgap of a quantum dot can be precisely controlled by its size, meaning that different sizes of quantum dots have different absorption band edges. It is therefore possible to synthesize quantum dots of various sizes that absorb most, if not all, of the sun's spectrum — something than cannot be achieved using the conventional approaches of crystalline silicon solar-cell fabrication. One can then envision a multistack solar cell in which the top layer absorbs the highest energy (shortest wavelength) photons and the bottom layer absorbs the lowest energy photons. This approach maximizes the absorption of sunlight by utilizing the photons that cannot be collected by single-layer crystalline solar cells. Although the multistack scheme can also be achieved using several different traditional semiconductor materials (each with a different bandgap), the big advantage of quantum dots is that a single material is used for all of the layers comprising the solar cell (except for the electrodes).

The electrons and holes generated in a solar cell must travel to their respective electrodes for the electrical potential to be useful and drive a load. The process of charge transport within quantum dot solar cells can be enhanced in several ways, including through the use of materials that provide quantum dots with a large Bohr radius mixed with (or in the proximity of) an electron-accepting and electron-transporting material



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In recent years, nanorods or armed tetrapods have been used to improve charge transport in quantum dots. Tetrapods consist of a core and four arms; varying the diameter of the arms allows the bandgap of the tetrapods to be tuned. One of the added advantages of the tetrapods is that they exhibit better solubility in a given solvent than the individual separate arms (nanorods).

such as TiO_2. The large Bohr radius allows the electronic wavefunction of the charge carriers generated in a given quantum dot to overlap with the neighbouring electron-accepting material, thus enhancing electron transport towards the collecting electrode.

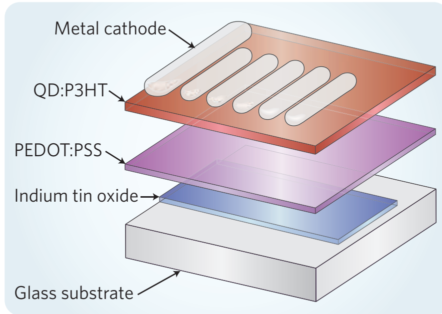
Researchers at Cavendish Laboratory in Cambridge, UK, have demonstrated that a tetrapod quantum-dot design improves charge transport. A tetrapod consists of a core and four arms, which can be tuned in length and diameter. Researchers at Rice University in Houston, Texas, USA, have also developed a method of synthesizing tetrapod-shaped quantum dots with high selectivity and uniformity at low cost. The tetrapod shape for cadmium selenide quantum dots is achieved when their synthesis is carried out in the presence of cetyltrimethylammonium bromide. Solterra has licensed Rice University's fabrication technology and is now scaling up production of the cadmium selenide tetrapod quantum dots through continuous microreactor technology to levels that support the production of solar cells with a rated cell output of greater than 1 GW. By using tetrapod quantum dots in a polymer matrix, Solterra has demonstrated power-conversion efficiencies of 6% from prototype cells with widths of ~0.1 m.

The polymer used in Solterra's cells provides a complementary method of light absorption for the quantum dots. This allows a wider range of wavelengths to be absorbed and thus more electron–hole pairs to be generated. After electron–hole separation, the electrons are transported by the quantum dots to one electrode while the holes are transported by the polymer to the other. It is critical, therefore, to shorten the distance between the quantum dots in the polymer matrix to achieve efficient electron transport.

Although the present efficiency values for quantum dot solar cells fall below those of inorganic technologies such as silicon, the use of an organic polymer matrix containing quantum dots allows simple solar-cell production at relatively low temperatures and low fabrication cost. Flexible polymer-based devices are particularly easy and cost-effective to fabricate as they involve techniques such as spin casting. Researchers at Arizona State University have developed roll-to-roll printing techniques for fabricating quantum dot and solution-based solar cells. At Solterra, we have used screen printing technology to fabricate our solar cells. Screen printing is a commonly used industrial technique for depositing dye films over large areas at high speed and low cost. In this respect it is an ideal technology for the large-scale fabrication of polymer-based solar cells. Screen printing also allows patterning to easily define which areas of the substrate receive deposition. This is important, for instance, for fabricating a photovoltaic device that is integrated on a substrate containing other electronic devices. Furthermore, in the production of a large-area energy-collection system, it is necessary to fabricate many individual solar cells and then wire them together. Screen printing allows individual devices to be easily defined on the same substrate for optimizing the power generation of the entire system.

Production costs and conversion efficiencies are the two main factors in calculating the total cost of a solar cell. Decreasing manufacturing costs and rising efficiencies are bringing down the costs of conventional cells. However, as a long-term solution to a much larger sustainable energy issue, there is some concern about the availability of certain exotic materials such as indium. Feedstock production for silicon-based solar cells certainly comes with very high cost and production-intensive demands, making it doubtful whether silicon-based cells can ever be scaled to the volumes needed to meet the increasing demands for clean energy. Although quantum dot solar cells currently use layers of indium tin oxide — a transparent conductive film used as an electrode — recent advances in carbon-nanotube-based conductive layers for displays show promise as an indium-free alternative. The use of such a material as a substitute for indium tin oxide is currently under consideration.

Besides lower production costs and higher efficiencies, widening the collection window of sunlight conversion can increase the output of fixed installations. Owing to their aforementioned size- and frequency-tuning



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The structure of a typical quantum dot solar cell. It consists of a layer of transparent and electrically conducting indium tin oxide of thickness 150 nm, which functions as an electrode and allows light to penetrate the solar cell. This is covered by a layer of the conducting polymer PEDOT:PSS spin-coated on top at a thickness of 40 nm, which is electron-blocking and provides hole injection to the indium tin oxide layer. The quantum dot/polymer layer (QD:P3HT) is either printed or spin-coated, and is usually 25–70 nm thick. The polymer used in this case is P3HT, and the quantum dots are cadmium selenide. A layer of metal on the surface functions as the second electrode.

capability, quantum dot solar cells can be used not only to absorb visible light under diffuse conditions, but also to convert radiated waste heat into usable electricity during dim light or dark conditions.

To make this vision a reality, Solterra is increasing its production of quantum dots to 100 kg per day and implementing a high-speed production line for printing solar cells at a rate of 300 m^2 per minute. We have also initiated plans to supply solar cells to a 1 GW solar farm in the Middle East that will supply both regional and European energy grids with a target date of 2015. Although the initial peak power rating for the completed modules will be lower than those of present inorganic photovoltaic technology, it is anticipated that due to their lower production costs, electricity generation will start at a near-typical grid pricing. Optimization of the cell layer design and introduction of improved materials is expected to provide further improvements in efficiency toward the theoretical maximum of 65%. This may ultimately lead to solar energy supplanting fossil fuel generation within 5–10 years. ❐

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