Bringing solar cell efficiencies into the light

Nanostructured materials are used in the development of a new generation of efficient solar cells, but challenges in the characterization and fabrication of these cells delay commercial adoption.

The success of photovoltaics as a renewable energy technology arguably rests on two numbers: the efficiency of conversion of solar energy into electricity and the cost per watt of produced power. Silicon solar cells, which command the largest market share, reach a power-conversion efficiency of 25.6%[1]; this value is reduced in commercial products, and cannot exceed 29%. Indeed, a fundamental limit introduced by Shockley and Queisser caps the efficiency of any solar cell based on a single p–n junction (a junction between positively and negatively charged volumes) to about 33% or less, depending on the bandgap of the material and on the illumination conditions[2]. Furthermore, silicon solar cells are expensive because of the raw materials used (monocrystalline silicon wafers) and the installation required. These cells are also rigid and relatively heavy. As a result, new materials and device architectures are actively sought.

Efficiencies higher than the Shockley–Queisser limit can be achieved by using more than one p–n junction, but the increase in device complexity also increases costs and limits adoption of this technology to niche applications. Issues of costs and flexibility are partially addressed by 'second generation' solar cells, which are made from thin films of semiconductors and can cover curved surfaces. However, typical commercial thin-film cells have much lower efficiencies of around 10–12%, and their efficiency drops with prolonged use.

Advanced materials and architectures can help overcome the limitations of conventional photovoltaic devices. Nanostructures, for example, can be used to design solar cells that are not based on planar p–n junctions and can, in principle, have efficiencies higher than the Shockley–Queisser limit. One such device is the quantum dot solar cell, which can generate more than one electron–hole pair per absorbed photon[3] and has the potential to increase the efficiency limit to 44%[4]. Although the efficiency of these cells has seen a 5% increase in just 4 years, at present it is still quite low (8.6%[5]). Nevertheless, quantum dot solar cells could also offer potential reductions in cost because they can be solution-processed.

Nanostructures can also be used to enhance the performance of existing photovoltaic devices by, for example, increasing the fraction of light that is available for conversion into electrical output. Nanostructuring the light-absorber layer with subwavelength features results in very low reflection and increased photon absorption[6]; this, in turn, can lead to higher cell efficiency without the need for additional antireflection coatings. However, large surface areas in nanostructures increase charge-carrier recombination, which is detrimental to efficiency, and so far silicon solar cells with nanostructured light absorbers — 'black silicon' solar cells — have reached an efficiency of only 18.2%[7].

Solar cells based on arrays of semiconductor nanowires can also demonstrate efficient light trapping, and could reduce material costs because less material is used than in planar cells. Efficiencies of up to 13.8% have, for example, been reported for InP nanowire cells[8]. Furthermore, it has been claimed that nanowire solar cells have the potential to exceed the Shockley–Queisser limit[9]. In particular, apparent efficiencies of 40% have been reported with a single GaAs nanowire cell[9], but while impressive, this is based on an absorption cross-section that exceeds the physical size of the nanowire, and raises concerns on how the efficiency should be defined for these kinds of cell.

Despite the potential of nanostructured solar cells to push efficiencies up and costs down, at present the efficiency of these cells is rather low. Moreover, several challenges must be addressed before these technologies can make it to the market and compete with silicon cells, which are rigid and expensive but also stable and efficient. Charge recombination due to large surface areas is only one of the issues faced by nanostructured solar cells. Some also have stability issues: exposure to air or an inert atmosphere can significantly degrade the performance of solution-processed quantum dot solar cells[10]. Although progress is being made[5,11], further insight into the physical mechanisms is needed to exploit the potential of nanostructured solar cells. Furthermore, most solar cells fabricated in research labs have small active areas, and it is unclear whether high efficiencies will be maintained when they are scaled to large areas for industrial production.

Small cell size and instability can also hinder independent certification of the efficiency values by the National Renewable Energy Laboratory (NREL), the Fraunhofer Institute for Solar Energy Systems, or similar institutions that test solar cells under standard conditions, collecting data on the spectral responsivity and on the current–voltage characteristics. From the latter the power-conversion efficiency is calculated, and the highest values for each technology are reported on a chart[12] and in tables[1]. This allows the performance of competing technologies to be compared on equal footing, and validates claims of record efficiency for novel technologies. However, to achieve certification the device operation must remain stable for the time it takes to send it off to an accredited laboratory and get it tested.

For *Nature Nanotechnology*, the standardization and accuracy of reported efficiency values is considered a priority in photovoltaics research; a view shared by other *Nature* research journals. The September issue of *Nature Materials*, for example, discusses problems in the characterization of perovskite solar cells, a technology for which some of the highest efficiencies reported have been overshadowed by doubts about the ways the values were measured[13]. Overestimation of device performance also affects the organic and hybrid solar cell communities, as an editorial in the September issue of *Nature Photonics* reports[14]. At *Nature Nanotechnology*, we strongly encourage authors to provide certified efficiency values wherever possible. In any case, sufficient details of electrical characterization must be reported to unambiguously describe the methods used, and allow others to check the validity of the claimed efficiency values. ❐

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