

PHOTOVOLTAICS

Perovskite cells roll forward

Reports of perovskite solar cells fabricated at temperatures compatible with polymer substrates indicate that high-performance flexible cells are now an exciting proposition. However, increasing the cell area and stability and addressing environmental concerns are aspects requiring attention.

Gary Hodes and David Cahen

Hybrid organic–inorganic perovskites, most commonly $\text{CH}_3\text{NH}_3\text{PbI}_3$ or a close variant, were first introduced to the photovoltaic community in 2009¹. In subsequent years, cells based on such materials have shown an unprecedented increase in solar-to-electrical power conversion efficiency — from <10% in mid-2012² to over 15% at present^{3,4}. Although all the demonstrations have been for small-area (<1 cm²) devices, it is quite remarkable for cells based on a material that is new to photovoltaics to perform so well so quickly. Indeed, technical issues related to commercialization of the technology, which usually attract attention only after many years of research, are already being considered.

One issue that is especially pertinent to the commercialization of perovskite cells is the cost (both in terms of energy and money) and complexity of their fabrication. In this regard, perovskites seem very promising, because they can be made by deposition from organic solutions at low temperatures (temperatures from 150 °C down to room temperature have been used) and yet form a material with high crystalline and electronic quality. Most other parts of the cells (see Fig. 1) can also typically be fabricated by low-temperature solution methods. However, the fabrication of one of the central components — the electron-selective contact — usually requires a fairly high temperature (~500 °C) sintering step. This is composed of a planar layer onto which a nanoparticle layer is usually deposited; both layers are commonly made from TiO_2 and require a separate sintering step. These layers allow electrons to flow, but block holes.

Several approaches that help circumvent this limitation have recently been demonstrated. Initially, alumina nanoparticles were used instead of TiO_2 ; this allowed the nanoparticle layer to be sintered at a lower temperature (<150 °C) and gave efficiencies of over 12%, although a planar TiO_2 layer sintered at a high temperature was still required⁵. Using ZnO

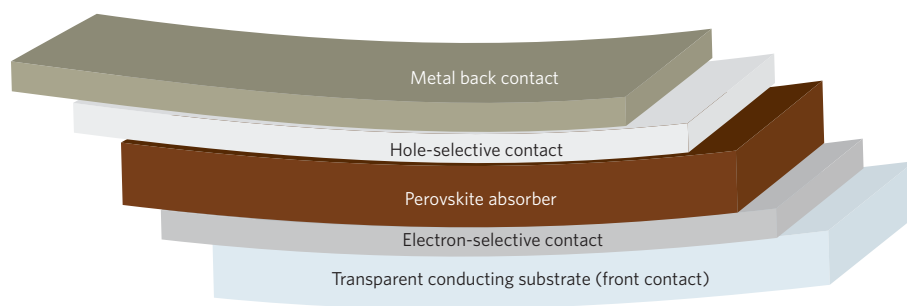


Figure 1 | Schematic of a perovskite photovoltaic cell. The perovskite light-absorbing layer (brown) is sandwiched between two charge transport layers (grey) that selectively pass electrons and holes to electrical contacts on the front and back of the cell, respectively, to form a current. In inverted cell structures, the electron- and hole-selective contacts are interchanged with respect to the transparent front contact.

as the electron-selective contact permitted both the planar and nanoparticle layers to be processed at low temperatures. Employing this idea, Kumar *et al.*⁶ reported nearly 9% efficient cells that were fabricated using processing temperatures below 100 °C. A more recent report⁷ describes a so-called inverted cell structure (light first passes through the hole-selective contact instead of the electron-selective contact) with a perovskite layer sandwiched between two organic contacts. The cells were processed at temperatures up to 150 °C and exhibited a conversion efficiency of 10%.

The lower processing temperatures used to produce these cells open the way to fabricate solar cells on flexible substrates such as polymers. Indeed, flexible cells fabricated using these approaches with efficiencies of 2.6% (ref. 6) and 6.4% (ref. 7) have since been reported in the literature. It also appears that more reports of flexible perovskite cells are in the pipeline, based on the presentations at a special session of the Fall Materials Research Society meeting⁸ held in early December 2013 in Boston, USA. Of the many potential advantages of flexible cells, the possibility of roll-to-roll processing, long used for many large-scale

manufacturing processes, is probably the most significant.

Two papers concurrently published in *Nature Photonics* reveal the fast progress that is being made in realizing low-temperature processed and flexible cells with increasing levels of performance. Malinkiewicz *et al.*⁹ describe an inverted planar cell where both selective contacts are organic semiconductors that were deposited at ambient temperature (the iodide perovskite was sublimed); this cell has a conversion efficiency of 12%.

In the other report, Liu and Kelly³ use a planar geometry with a thin planar ZnO layer and what appears to be a maximum processing temperature of 65 °C to achieve an efficiency close to 16% for cells on rigid indium tin oxide substrates — a performance similar to that of the best perovskite cells made to date. The same paper also reports a cell on a flexible substrate with an efficiency of just over 10%. The increase in efficiency of flexible perovskite cells from 2.6% to the present 10.2% occurred over a mere five weeks (based on paper submission dates). Such rapid progress is indicative of the speed at which perovskite solar cell research is advancing.

The Malinkiewicz *et al.* report also describes the effect of increasing cell area on the cell efficiency. Almost all the best-performing cells reported to date have areas of $<0.1 \text{ cm}^2$. However, the ability to make large-area devices reproducibly is critical in practice. Malinkiewicz *et al.* compared large (1 cm^2) cells with standard-size (0.09 cm^2) cells and found (for non-flexible cells) that the conversion efficiency dropped from 12% for the small cells to 8.3% for the large ones. Most of this reduction in efficiency results from a decrease in the fill factor (which defines the shape of the current–voltage plot of the cell). Possible reasons for this loss in the fill factor were not discussed and are currently unclear. Perovskite inhomogeneity is unlikely to be the cause for this loss as the perovskite films were evaporated, which normally results in a more homogeneous film thickness than the more commonly used solution deposition.

Although the eye-catching 10.2% efficient flexible cell reported by Liu and Kelly may attract most attention, we think that the report of a $>8\%$ 1-cm^2 -sized cell, is at least as significant a milestone in perovskite photovoltaic research. This follows a report¹⁰ earlier in 2013 of a 15% cell with an area of almost 0.3 cm^2 .

Low-temperature processing and cell flexibility are undoubtedly useful and

important, but there are other factors besides scaling cell area that need to be resolved before perovskite cells can realize their expected potential. One is the issue of stability. There has been only one report that provides encouraging data regarding the stability of operating cells¹⁰. Although long-term stability may well be attained, there is currently insufficient information on this aspect. The good news is that liquid-electrolyte dye-sensitized cells can be reliably encapsulated, enabling them to last years without degradation. Because it is very difficult to encapsulate an organic electrolyte that has a highly active redox couple, this achievement suggests the feasibility of realizing proper encapsulation that can keep out moisture, oxygen and ultraviolet radiation.

A further concern is the environmental one, as perovskite cells contain lead. Lead is not a critical, scarce material, but it is toxic and definitely needs to be kept out of the environment. Here, perovskites differ from CdTe-based cells in that the latter do not contain cadmium in a readily soluble form. This is important because, for example, the encapsulation may rupture allowing rain to come into contact with the bare cell; it is not clear how easily lead ions would enter the environment in such a scenario.

The great excitement in the photovoltaic community about perovskites, as reflected

by the many groups who have started working in this field in the past two years, is justified. This community has never before witnessed such a rapidly advancing technology with genuine promise for commercialization. The recent reports of low processing temperatures and the use of flexible substrates only increase the attractiveness of this technology. It is hoped, even expected, that the remaining issues, including scaling up of cell area and improved cell stability, will be more intensively investigated and satisfactorily resolved in the near future. □

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OPTICAL MATERIALS

Silicon carbide's quantum aspects

An engineered defect in silicon carbide that acts as an artificial molecule is found to be the brightest room-temperature source of single photons presently available in a bulk material. This finding suggests that silicon carbide has a promising future for applications in quantum information processing.

Alberto Boretti

First discovered in its natural form in a meteorite in 1893, silicon carbide (SiC), also known as carborundum, is a compound semiconductor with attractive electronic and mechanical properties. It has received considerable attention for use in high-temperature and high-voltage semiconductor electronics as well as being widely used as an abrasive. However, in-depth studies related to the photonics applications of SiC are scarce, which is surprising given the fact that the very first reports of electroluminescence and a working light-emitting diode (LED) in the early twentieth century were of samples made from SiC. In 1907,

Henry Round published a brief note in *Electrical World* reporting light emission from carborundum and “other substances”, which he discovered while working on cat's whisker detectors at the company Marconi¹. Then, in 1927, Oleg Losev observed light emission from carborundum point-contact junctions, which were the first LEDs². Indeed, SiC was a popular choice for yellow and blue LEDs until gallium nitride, with its superior efficiency, took over in the 1990s. Today, its use in photonics is largely confined to a substrate material with excellent heat-dissipation properties.

However, Castelletto and co-workers have now found that SiC could be highly

valuable for applications in quantum optics, thanks to its ability to support atomic-scale defects that emit single quanta of light³. When this ability is considered in conjunction with SiC's optical transparency, high refractive index and compatibility with micro and nanofabrication techniques, it looks like SiC may soon enjoy a renaissance in photonics and become a popular material for the next generation of integrated sensors that rely on quantum-physics effects.

Castelletto *et al.* are the first to integrate single individually optically addressable defects in ultrapure SiC, which provide