Use of a perovskite layer to boost the efficiency of CIGS modules

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ABSTRACT

Perovskite microcrystals have properties that make them uniquely suitable as a basis of thin, light, semi-transparent solar modules. However, there are some remaining challenges, including lifelong stability, that need to be tackled before this technology can become commercially available. Once these have been resolved, perovskites can also be deployed for boosting established solar technology, such as silicon or copper indium gallium selenide (CIGS) modules. As an example, a record efficiency of 17.8% has recently been reported for a stacked perovskite/CIGS module, surpassing the highest efficiencies achieved so far for both stand-alone perovskite modules and CIGS modules.

Introduction

Perovskite microcrystals are a promising material for manufacturing high-yielding thin-film solar cells. Although these microcrystals have excellent properties, they also present a number of challenges, especially with regard to stability. Perovskites can be processed into thin, light, semi-transparent modules that could eventually be integrated in building materials, such as windows or curved construction elements. In addition, they can be used to enhance established solar technology, such as silicon or copper indium gallium selenide (CIGS) modules. A record efficiency of 17.8% was recently reported [1] for a stacked perovskite/CIGS module (Fig. 1), surpassing the highest efficiencies achieved so far for both stand-alone perovskite modules and CIGS modules.

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Imec started its R&D in perovskite solar cells in 2014, with an emphasis on developing a scalable, stable and lead-free technology [2,3]. This research is embedded within Solliance [4,5], a transnational partnership between expert companies and research institutes collaborating on thin-film solar technology. Imec's PV research is part of EnergyVille, the Flemish expertise centre for energy technology.

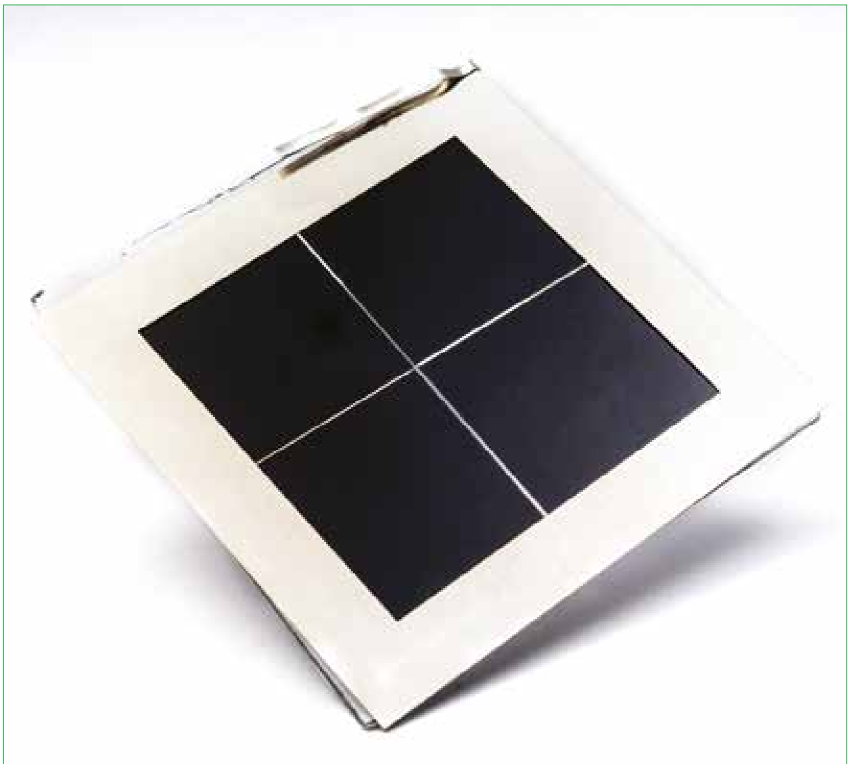

Figure 1. Module of stacked perovskite on CIGS technology.

Searching the perovskite grab bag for gold

Perovskite solar cells are made up of a carefully engineered stack of functional layers, with a central photoactive layer made from microcrystals of perovskites. Perovskites comprise a well-known family of materials that form microcrystals with the structure ABX_3. Solar cells typically use an organometal halide perovskite, in which material A is an organic cation, material B is a metal ion (such as lead), and X is a halide anion (such as iodide, bromide or chloride).

With these three elements, a great many variations of perovskites may be engineered, each having specific characteristics; some of these perovskites will be very useful in harvesting solar energy, others less so. However, there is no direct way of knowing in advance which will be best suited to solar cells. An element of the R&D work therefore entails painstakingly screening compounds and their behaviour, literally searching the perovskite grab bag for gold.

The first use of perovskites in solar cells dates back to only 2009, when they were integrated using a dye-sensitized solar cell architecture, generating a very modest 3.8% conversion efficiency. Moreover, these cells were only stable for a few minutes before they degraded. Since then, labs around the world have steadily improved the efficiency, now achieving values of around 20% in lab cells, with the expectation of even higher values in the future.

Excellent properties, but stability needs improving

Apart from their efficiency, perovskite solar cells have many desirable properties. For example, they are potentially cheap to produce, because they can be constructed using simple fabrication techniques, such as coating and printing with ink-like materials on flexible or glass substrates. In addition, perovskite layers have a high absorption efficiency for sunlight; consequently, not much of the material is needed, a layer of at most a few hundred nanometres being sufficient.

As previously mentioned, the microcrystalline material can be carefully engineered to achieve various optical and electronic properties. This allows, for example, the colour and transparency of the cells to be adjusted, depending on how and when they will be used. However, it also allows a spectrum to be chosen that is complementary to the absorption spectrum of another type of PV technology, such as cells based on silicon or CIGS materials. With semi-transparency and complementarity absorption, it therefore becomes possible to design tandem cells – stacks of solar cells based on different technologies.

The benefit of perovskite solar cells is that the bandgap can be tuned by adjusting, for example, the amount of bromine (Fig. 2). In this way, a solar cell with a bandgap of around 1.8eV can be created; according to calculations, this produces the best combination with a silicon solar cell (to achieve an efficiency higher than that of the silicon solar cell alone).

Whereas the efficiency of perovskite-based PV has dramatically improved, the cell stability has not followed suit: perovskite cells still degrade too quickly, lasting only weeks or months instead of years or decades.

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One of the challenges is to make the perovskite layer stable under higher temperatures; currently, the material remains stable only for operating temperatures of up to 80°C. Together with a university group that specializes in engineering materials (IMOMEC at Hasselt University, Belgium), the researchers at imec have been developing new perovskite compounds which should remain stable up to 150°C. In parallel, imec is also refining the processing techniques in order to optimize the microcrystalline structure of the active layer.

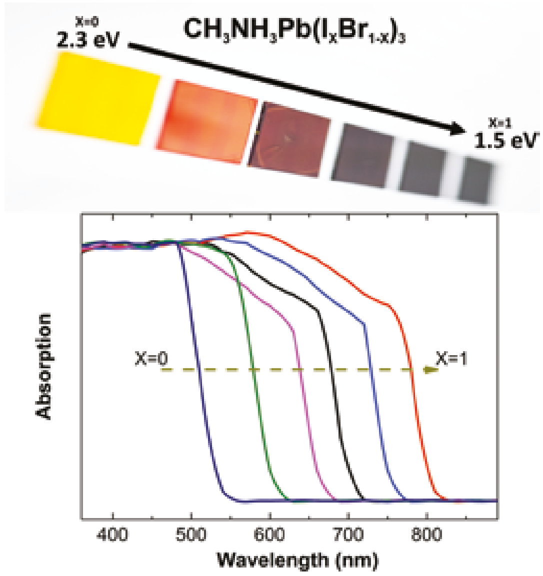

Figure 2. Tuning the bandgap by adjusting the amount of bromine in a perovskite solar cell.

A second issue concerns the hole-conducting layer; this is the layer that guides the holes to the contacts after they have separated from the electrons in the perovskite active layer. In the case of perovskite solar cells, typically a so-called *spiro layer* is used, a layer that was developed for dye-sensitized solar cells. However, being organic, this material degrades rather fast; alternatives are therefore needed here as well.

In addition, the best perovskite materials available today are still very sensitive to moisture, greatly limiting their outdoor use. One way to overcome this is to finish the PV stack with an excellent moisture barrier, for example by sandwiching it between two glass plates.

Unrelated to stability, but also very important, is the concern of toxicity of the material, particularly since the perovskites in use today contain lead. Although the concentration in final PV systems will be very low, it is vital to find a lead-free material with good stability in order to produce a sustainable PV technology and consumer products that adhere to the WEEE (waste electrical and electronic equipment) and RoHS (restriction of hazardous substances) regulations.

On all these issues, imec is slowly making progress, carefully tuning the recipes and processing steps. It is expected that, as in the case of efficiency, advances in the stability of the technology will also be made, with the achieved lifetimes measured in years rather than weeks.

From stand-alone to tandem modules

Cells are one thing, but if it is ever hoped to get this technology out of the lab and into production, it is essential to develop processes that can be scaled to an industrial level. This means processing large-area cells with good efficiencies, and integrating cells into modules without much efficiency loss, as well as eventually integrating them in fully fledged PV systems.

Recently, in May 2016, the team at imec presented the first-ever semi-transparent perovskite PV modules. These were fabricated with scalable coating techniques, and demonstrated efficiencies of 12% on sizes as big as $4cm^2$ and 10% on sizes as big as $16cm^2$, which was a world best for such large areas. Comparable modules may be realized on flexible (plastic film or metal foil) carriers as well as on rigid (glass, metal) carriers. In addition, by carefully mixing in the right materials, the optical and electrical properties of the cells may be tuned, which also results in colour and transparency variations at the module level.

Aside from making perovskite layers that are transparent, it is also possible to engineer them to absorb specific spectral ranges. If this is done, the layers will be found to have a sharp absorption cut-off, meaning that there is very little parasitic absorption from nearby spectral ranges. This naturally leads to the idea that perovskite cells could be stacked on top of other solar cells, such as silicon cells or other thin-film cells.

Using silicon PV, imec has managed to stack a transparent perovskite

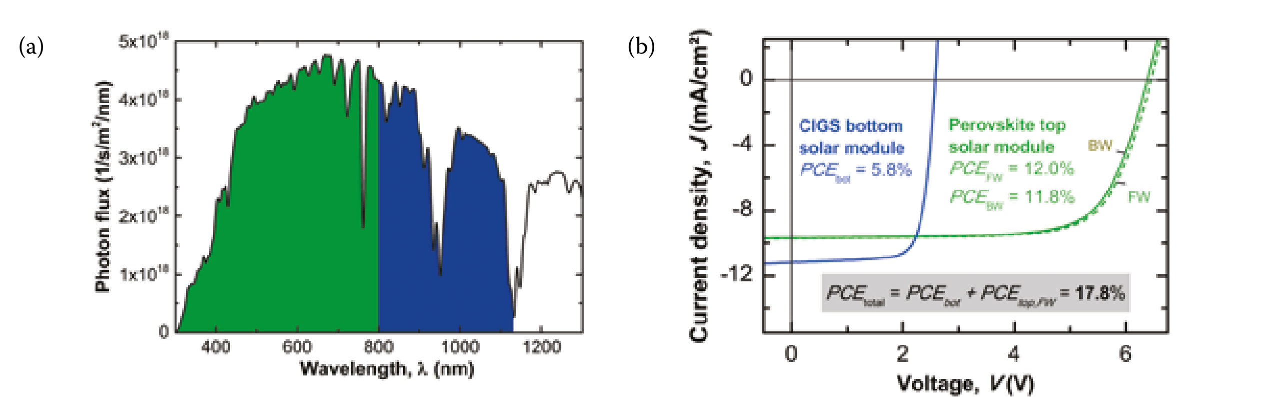

Figure 3. (a) AM1.5 photon flux, with coloured wavelength regions representing the spectral range that is harvested by the perovskite top solar module (green) and the CIGS bottom solar module (blue). (b) *I–V* characteristics of the stacked perovskite top solar module and the CIGS bottom solar module.

module on top of interdigitated back contact (IBC) silicon solar cells of the same size. In this set-up, the perovskite top module passed 70% of the incoming light to the silicon cells. In this way, a conversion efficiency of 20.2% was measured for a 4cm^2 stack and 17.2% for a 16cm^2 stack, a record result for this size.

One of the challenges of combining technologies is that it is preferable to work with state-of-the-art expertise and technology, and these are rarely found at a single lab. For the next combination that will be discussed, perovskite on CIGS, imec therefore worked together with an international team, resulting in the announcement of another record-performing module.

Perovskite on CIGS modules

CIGS is an established thin-film PV technology: the current world record for stand-alone CIGS cells stands at 22.6%, and was established at Germany's ZSW (Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg). The scientists at imec therefore teamed up with those at ZSW and at another German lab at the Karlsruhe Institute of Technology (KIT). KIT focuses on the optics in multijunction perovskite solar modules and develops specialized nanophotonic materials for these devices.

The result of the work carried out for this project was a thin-film stack with a conversion efficiency of 17.8%; this was realized mainly by efficiently exploiting the solar spectrum (Fig. 3). The higher-energy part of the spectrum is harvested by the semi-transparent perovskite module on top, while the lower-energy light passes through and is harvested by the bottom CIGS module. The stack, with an efficiency of 17.8%, outperforms imec's world-record upscaled perovskite module (efficiency of 15.3%), as well as the highly efficient stand-alone upscaled CIGS module from ZSW (efficiencies near 15.7%).

The new module (3.76cm^2) makes use of the so-called *4-terminal architecture*, where a perovskite solar module in superstrate configuration is stacked on a CIGS solar module in a substrate configuration. Both submodules are constructed using a fully scalable interconnection scheme, offering a route towards solar modules on the scale of a few square metres.

To see what the maximum potential of this technology might be, imec has quantified the various losses still present in the presented prototype, and also identified the key challenges and possibilities of eventually reaching power conversion efficiencies above 25%.

"Perovskite solar technology is definitely a solid contender for inclusion in the PV technology mix that will power our future world."

Outlook: a perovskite-powered environment

Perovskite solar technology is definitely a solid contender for inclusion in the PV technology mix that will power our future world. Perovskite has demonstrated its potential both as a booster material for various other technologies, and as an inexpensive technology for powering up large surfaces in, for example, buildings or cars. The next few years will tell if the right mix of efficiency, stability and scale can be formulated which will lead to large-scale application of this fascinating and very versatile material.

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About the Author

Tom Aernouts heads the thin-film PV research at imec. After obtaining his Ph.D. in physics from KU Leuven (Belgium), he began his research career at imec, working on organic oligomer-based diode structures and organic PV. He has overseen the group's successful growth in manpower, expertise and covered thin-film technologies, while authoring or co-authoring more than 80 journal publications, book chapters and conference contributions.

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