[Strapline:] Solar cells

[Online title:] Solar cells that combine multiple perovskite layers surpass 30% efficiency

[Print title:] Perovskite solar cells surpass 30% efficiency

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[Standfirst:] Perovskites are promising materials for solar cells. A layer of dipolar molecules at the perovskite surface improves the efficiency of these devices. See p.xxx

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Rooftop solar panels, which are generally made of crystalline silicon, can convert around 25% of the energy from sunlight into electricity. A class of semiconductors called metal halide perovskites has been proposed as next-generation solar cell materials, with the potential to achieve efficiencies that are not possible using only silicon. ‘Tandem’ solar cells, in which different perovskites are layered on top of each other, are a particularly promising approach. However, unwanted heat generated by crystal defects in the perovskite bulk and at interfaces between the perovskite and charge collection layers takes part of the energy from incident light, limiting the power conversion efficiency of these devices.

Writing in *Nature,* Lin *et al.*[1] report tandem perovskite solar cells that use surfactant molecules on the perovskite surface to reduce interface energy loss. The resulting solar cells convert more than 30% of incident solar energy into electrical energy, surpassing the ultimate theoretical limitation for silicon solar cells.

Solar cells convert light to electricity through a process called the photovoltaic effect, in which photons transfer energy to electrons that are bound to atoms, promoting them to higher-energy levels in which they are free to move through the material. The liberated electron also creates a ‘hole’ in the lower energy level, which behaves like a positive charge. The solar cell has a built-in electric field that generates a current by separating the electrons and holes of the device under illumination.

The minimum energy needed to promote an electron from a bound to a conducting energy level is approximately equivalent to a property of the material called bandgap. The bandgap of a given material determines the photon frequency (colour) that it can convert into electricity.

If the photon has more energy than the bandgap, excess energy is released mostly as heat. Furthermore, electrons and holes can become trapped at lattice defects, where they recombine with each other through an effect called non-radiative recombination. When this occurs, the electrons and holes no longer contribute to the generation of electricity -- instead, their energy is released as crystal vibrations called phonons. These two sources of energy loss are the main factors which have limited most solar cells’ efficiency to less than 30%.

Perovskites are materials that have the chemical formula ABX_3. These materials have the potential to generate more energy when used as solar cell materials, and their bandgap can be tuned by altering their composition. Perovskite materials can also be made into thin films at temperatures that are over ten times lower than those required in the production of traditional solar materials such as silicon.

The first perovskite solar cell was reported in 2009, and was made from a type of perovskite called a lead-halide perovskite[2]. Perovskites have since been integrated into tandem solar cells, in which layers of two or more materials that have different bandgaps are stacked on top of one another. Viewed from the side on which light is incident, the upper layer of the stack absorbs higher-frequency light than the bottom of the stack. This enables energy to be harvested from a wide range of wavelengths more efficiently than with a single perovskite layer[3–5]. Perovskite solar cells extract electrons and holes using ‘charge extraction layers' on the top and bottom sides of the perovskite layer(s)[6]. Electrons are extracted through one layer, and holes are extracted through the other. The tandem solar cell reported by Lin and colleagues had the narrow- and wide-bandgap perovskite layers, both individually switched with the hole electron extraction layer below and electron extraction layer above. Then, an interlayer, called the recombination junction, is inserted between these two subcells to allow the flow of the generated charge.

A subclass of metal-halide perovskites called ‘mixed tin–lead (Sn–Pb)’ perovskites can be tuned to have a bandgap close to crystalline silicon[7,8].

However, these perovskites often exhibit high densities of defects. This means that nonradiative recombination at the interface between the mixed Sn–Pb perovskites and the charge carrier extraction layers is a source of high energy loss.

Modification to a material that reduces the effect of defects is called passivation. Building on previous work on passivation of the interface through which electrons are extracted[9], Lin *et al.* focused on improving the hole-extracting interface of mixed Sn–Pb perovskite solar cells.

The authors introduced a layer of organic surfactant between the narrow bandgap perovskite and the hole extraction layer. The surfactant molecules were dipolar, meaning that they have a positively charged and a negatively charged end. The positive end was directed toward the perovskite layer, and the negative end towards the hole extraction layer. These molecules and their oriented assembly simultaneously passivated defects within the perovskite lattice and enhanced the efficiency of charge carrier flow out of the perovskite layer.

This modification yielded roughly a threefold improvement in the “optoelectronic quality” of the perovskite film and the hole extraction rate at the interface. The authors fabricated solar cells from a single photoactive absorber layer (called single junction), narrow bandgap Sn–Pb perovskite films, achieving a high power conversion efficiency of 24.9%. They also constructed ‘double-junction’ tandem solar cells in which the narrow bandgap perovskite subcell was stacked on top of a wide bandgap perovskite subcell, achieving a power conversion efficiency of 30.6% -- about eight times higher compared to the first perovskite solar cells.

The surface modification reported by Lin and colleagues is expected to be effective even in more complex device architectures — such as triple- and quadruple-junction devices[10]. This could enable these devices to generate more electricity per unit area than conventional silicon solar cells, reducing the land required for solar farms. Moreover, the ease of fabrication and lightweight nature of perovskite thin-film solar cells make them suitable for diverse applications, from integration onto buildings to portable uses in backpacks, vehicles, aeronautics and space.

Some limitations remain, however. The material used for the hole extraction can catalyse the degradation of the Sn–Pb perovskite materials, which shortens the lifespan of the devices. Furthermore, the tandem solar cells the researchers fabricated had a light-collecting area of just a centimetre square or less. Scaling up these high-efficiency devices presents a challenge, because maintaining uniform performance across large-area perovskite devices is difficult[11].

An even greater task lies in improving the operational stability of these multilayered devices when subject to light, heat and the stresses of real-world deployment. From a materials science perspective, the focus should be on developing more stable perovskite materials; ensuring that the other layers are transparent and chemically inactive; and creating durable device encapsulation methodologies and materials. Refinements to the device design and the electronic properties of the different layers should also be explored to optimise the flow of light and charge. Such developments must also consider whether each layer is safe to produce, scalable, sustainable, made from abundant materials, and suitable for automated manufacturing.

It has been estimated that, to meet climate goals, the global energy generation capacity from solar cells will need to be around 75 terawatts (TW) by 2050[12]. If the material and manufacturing challenges are overcome, all-perovskite tandem solar cells will be able to contribute to this target -- converting more and more of the Sun’s energy into electricity and bringing affordable power to more corners of the world.

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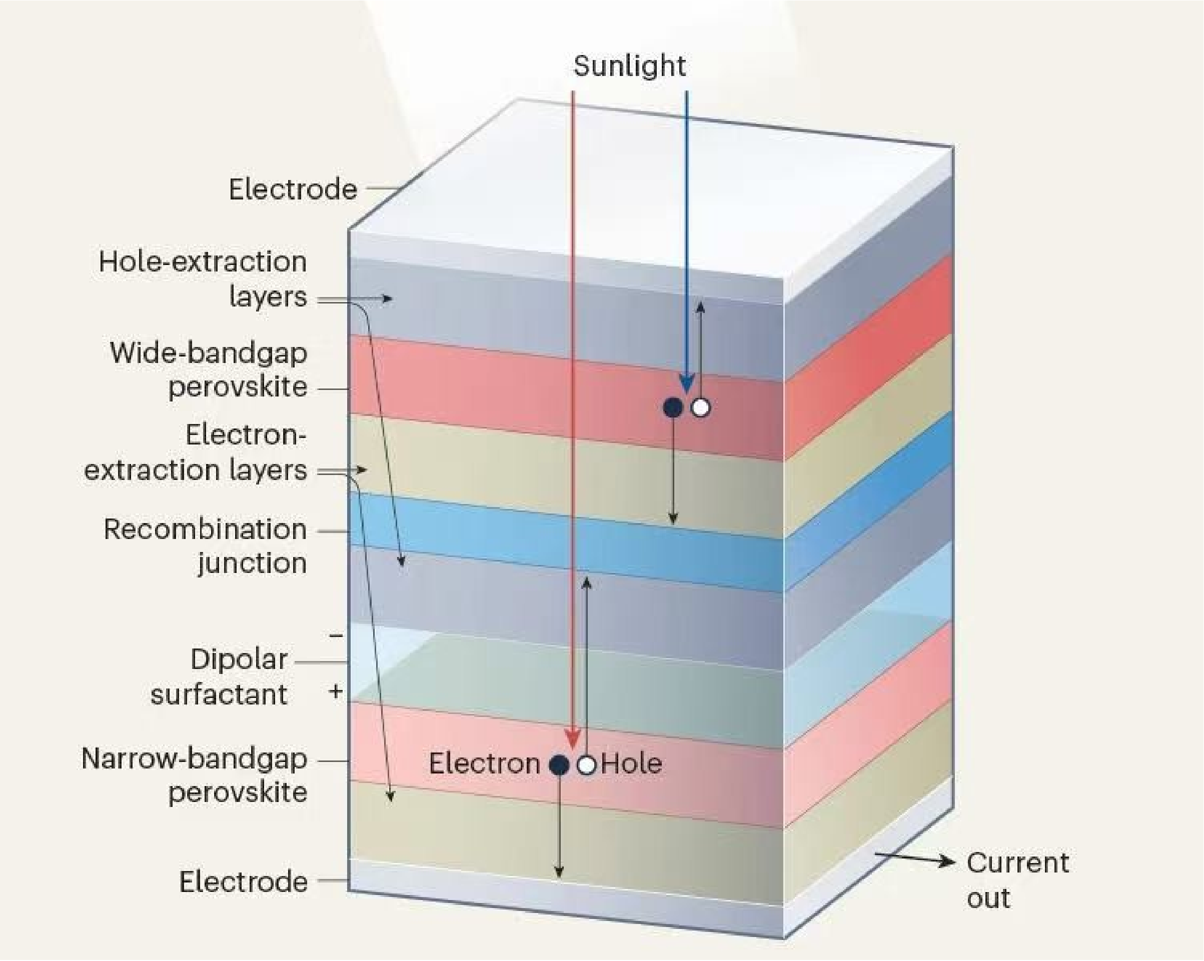

Figure 1 | All-perovskite tandem solar cell. A solar cell converts sunlight into electricity. Incident light causes electrons to be promoted to a higher energy level, leaving an empty space, or hole, behind. The minimum energy required to do this is called the bandgap. Lin *et al.*[1] report ‘tandem’ solar cells in which light is collected by two perovskite layers – one with a wide bandgap and the other a narrow bandgap. Electrons and holes are separated using extraction layers. A recombination junction layer enables electrons and holes to flow between the sub-cells. A voltage is applied using electrodes, which enables the current to flow out of the device. The authors use a dipolar surfactant between the hole extraction layer and the narrow bandgap perovskite layer to improve the hole extraction efficiency and decrease the effect of defects, which can cause a process called non-radiative recombination that reduces the efficiency of the device.