Converting Sun's energy with less accompanying heat

Shuaifeng Hu & Henry J. Snaith

Photovoltaic devices convert sunlight into electricity, yet a considerable portion of the energy is inevitably dissipated as heat. Advancements in perovskite materials and thin-film device integration technology make a major breakthrough in overcoming these losses. **See p.xxx**

Solar cells convert sunlight into electricity through a process known as the photovoltaic effect, and their efficiency in doing so depends primarily on the materials used and the device's design. On page **xxx**, Lin *et al.*[1] report an improved, less defective, narrow-bandgap (approximately 1.25 eV) material used in a device where the high-energy light is taken by another wide-bandgap (approximately 1.8 eV) material stacked in front. **As a result of "heat loss reduction", the thin-film perovskite solar cells, just two micrometres thick — over 70 times thinner than silicon — convert more than 30% of incident solar energy into electrical energy, surpassing the ultimate theoretical limitation for silicon solar cells – today's incumbent technology.**

Today's rooftop solar panels are made of crystalline silicon, and the devices convert around 25% of the energy from sunlight particles, photons, into electricity, thanks to about 70 years of development since their invention in 1954. During the conversion, high-energy photons — such as blue and green light — carry more energy than the silicon cell needs to free an electron from the valence band to the conduction band (about 1.1 eV, the bandgap of crystalline silicon). This excess energy is released as **heat** as the generated charge carriers — electrons and holes (positively charged quasiparticles) — relax to band edges. Instead of contributing to electric current, charge carriers can also be depleted at energy trap states created by lattice defects through so-called "non-radiative" recombination, releasing their energy as phonons — perceived as **heat**. These are the main factors which limit the silicon solar cells' efficiency to less than 30 per cent (**Figure 1a**).

The emergence of perovskite materials and so-called "multijunction" device technology is transformative. The first use of perovskites in solar cells was demonstrated in 2009 (ref.[2]), and their integration into highly layered, or multijunction, devices was achieved only about a decade ago[3–5]. Perovskites, from early on, exhibited surprisingly high open-circuit voltages[6] and have tunable band gaps by simply altering the composition of their ABX_3 formula. Among various compositional combinations, the bandgap can be tuned as low as 1.2 eV (similar to silicon) by substituting about 50% of lead (Pb) with tin (Sn) at the B-site[7], forming a subclass of perovskites named "mixed Sn–Pb" perovskites (**Figure 1b**). In this mixed perovskite, the valence band maximum is primarily derived from the high-lying Sn 5*s* orbitals, while the conduction band minimum mainly originates from the low-lying Pb 6*p* orbitals, resulting in a bandgap smaller than that of either neat case[8]. Beyond tuning their bandgaps, perovskite materials can also be readily made into thin films — by coating from a precursor solution, evaporating precursors under vacuum, or using a "hybrid" of the two methods — all at relatively low temperatures of just a few hundred degrees Celsius. By stacking two or more perovskite thin films with complementary bandgaps, these devices can capture a broader range of sunlight more efficiently. The upper layer(s) absorb high-energy blue to visible light, while the lower layer(s) collect the near infrared light, achieving better energy matching between sunlight and the bandgap of photoactive materials, and thereby reducing heat loss.

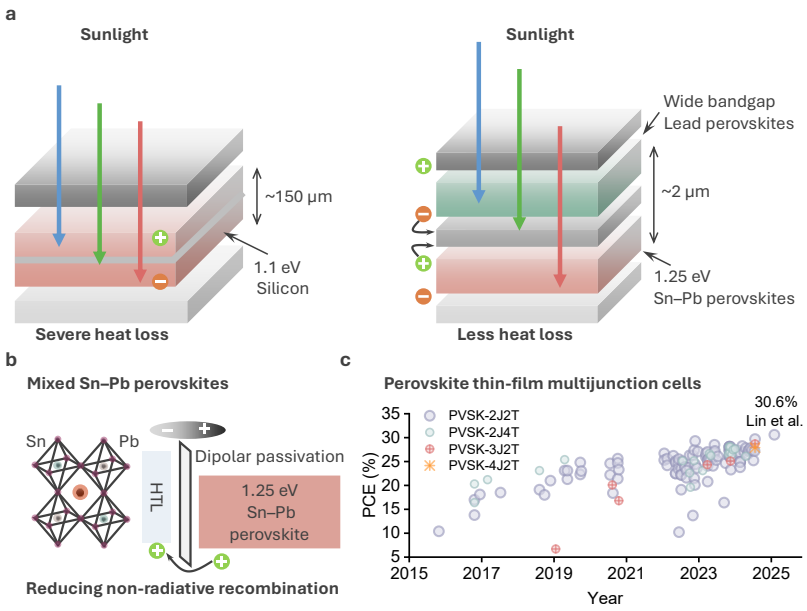

Figure 1 | Thin-film perovskite solar cells. a, Conventional silicon cells with severe heat loss from the high-energy light (left). Stacked thin-film perovskite solar cells split the light absorption and energy conversion with less heat (right). **b,** "Dipolar passivation" to reduce the generation of photons for well-performing Sn–Pb perovskite cells. HTL: hole transport layer. **c,** Efficiency evolution of perovskite thin-film cells. PVSK: perovskite, T: terminal, J: junction. PCE: power conversion efficiency.

From a materials perspective, enhancing the quality of narrow-bandgap Sn–Pb perovskites is crucial for improving sunlight-to-electricity conversion in this class of thin-film devices, as these materials often suffer from high defect densities and inefficient charge extraction at their interfaces. Building on previous n-side interface passivation[9], Lin *et al.* focus on improving the p-side (hole-collecting) interface. They show that introducing an organic surfactant containing both positively and negatively charged ends (a dipolar molecule) — directed toward the upper perovskite layer and the underlying hole transport layer, respectively — can simultaneously passivate defects within the perovskite lattice and enhance charge extraction through improved ohmic contact induced by surface dipoles. This dual effect yields roughly a threefold improvement in the "optoelectronic quality" of the perovskite film and the hole extraction rate at the p-side interface. As a result, Lin *et al.* achieve a record power conversion efficiency of 24.9% for single-junction Sn–Pb perovskite solar cells, and 30.6% in a double-junction, or "tandem" configuration, a factor of ten improvement since the first report of perovskite solar cells (**Figure 1c**). This achievement reflects how advances in both perovskite material quality and thin-film interface integration can substantially suppress heat loss by concurrently reducing phonon and carrier relaxation events.

Some limitations remain, however. The well-performing devices still rely on the use of acidic and hygroscopic hole transport material, poly(3,4-ethylenedioxythiophene) polystyrene sulfonate, which catalyses the photo degradation of the perovskite materials. Meanwhile, the researchers have only achieved/presented such high-power conversion efficiency using lab-scale devices. Scaling up these high-efficiency devices presents a major challenge, as maintaining uniform (opto)electronic quality across large-area perovskite films and devices remains difficult[10]. An even greater — and unavoidable — task lies in improving the operational stability of such a multilayered device under the combined stresses of light and heat, as well as under real-world deployment. This instability stems from a fundamental instability related to Sn-containing perovskites and from the multiple interfaces introduced during fabrication, roughly five times the junction number.

The implications are clear. The demonstrated modification is expected to be effective even in more complex device architectures — such as triple- and quadruple-junction devices[11] along with different electrical terminals[12] — which can, in principle, increase efficiency even further[13]. As a result, they

could generate more electricity per unit area, greatly reducing the land required for solar farms, or more rapidly reaching the required global photovoltaic generation capacity of around 80 terawatts for 100% renewable energy generation. Moreover, the ease of fabrication and lightweight nature of perovskite thin-film solar cells make them suitable for diverse applications, from integration onto building surfaces to portable uses in backpacks, vehicles, aeronautics and space. In many scenarios, everyday objects could serve as power sources whenever illuminated.

Before this, several challenges persist. From a materials science perspective, the focus should be on developing more stable photoactive perovskite materials, designing transparent and chemically inactive functional layers, and creating durable device encapsulation methodologies and materials. From a device engineering standpoint, further progress lies in improving how solar cells use light — by refining device designs and tweaking the electronic properties of their layers to manage light and charge flow better. From a manufacturing perspective, every layer must be safe to produce, scalable, sustainable and made from abundant materials, while also suitable for automation to achieve large-scale production with minimal energy input. Notably, moving towards a very high efficiency thin-film perovskite technology will overcome the main energy-intensive process of today's photovoltaic generation — production and refinement of silicon at around 2000 degrees Celsius.

Once these material and manufacturing challenges are overcome, future solar technologies could capture light of every energy with much less wasted heat, converting over half of the 'Sun's energy' into electricity — bringing affordable power to every corner of the world.

Shuaifeng Hu and **Herny J. Snaith** are in Clarendon Laboratory, Department of Physics, University of Oxford, Oxford, U.K.

e-mails: shuaifeng.hu@physics.ox.ac.uk (ORCID: https://orcid.org/0000-0003-1312-075X); henry.snaith@physics.ox.ac.uk (ORCID: https://orcid.org/0000-0001-8511-790X)

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