A Bright Future for Solution Processed Perovskite Light Emitting Diodes

Paul Meredith & Ardalan Armin

Department of Physics, Swansea University, Singleton Park, Swansea SA2 8PP, Wales, United Kingdom

Paul.meredith@swansea.ac.uk; ardalan.armin@swansea.ac.uk

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Standfirst: Light emitting diodes made from simple solution processed perovskite semiconductors have broken through the technologically important 20% efficiency barrier – are we seeing the birth of a new lighting and display technology, or will stability shortcomings outweigh the promised benefits?

Light emitting diodes, or LEDs have revolutionised lighting and displays. In an increasingly carbon-constrained world they deliver much greater energy efficiency than any previous 'light emitting' technology such as incandescent halogen and cold cathode fluorescent lamps. In addition, compound semiconductor 'micro-LEDs' are emerging which deliver unprecedented resolution for displays and organic semiconductor LEDs (OLEDs) provide unparalleled colour quality and near-180° viewing angles with the potential for flexible, lightweight form factors. In this issue of *Nature*, two papers simultaneously report what could be the birth of a new family of LEDs based upon an emergent class of semiconductor called the perovskites (PLEDs)[1,2]. These materials have recently 'shot to scientific stardom' predominantly for photovoltaics[3], but their potential in other applications such as photodetectors[4] and now LEDs is rapidly emerging[5]. Critically, the perovskites can be solution processed (by printing for example) and deliver optoelectronic performance in the simplest of planar 'sandwich' diodes. These features promise ultra-low manufacturing costs, low embodied energy, and the possibility of large area devices. Both Cao et al.[1] and Lin et al.[2] have broken through the 20% external quantum efficiency barrier (EQE- the ratio of the number outgoing photons to the consumed electrons) with their PLEDs. Why is this important? Well, efficiencies such as these rival mature OLED technology[6] – a feet achieved in <4 years from the first report of a PLED[5] with seemingly plenty of room for improvement based on the physics of perovskites.

There are several important similarities between the approaches of Cao et al.[1] and Lin et al.[2]: notably in both cases the active 'emissive' semiconducting layer (of order 200 nm) is sandwiched between two relatively simple current injecting electrodes appropriately modified to ensure electrons and holes are efficiently pumped into the perovskite to create electroluminescence. This is called a planar structure and is the most basic manifestation of a thin film diode (**Figure 1**). In addition, the perovskite layers are solution processed and the resulting semiconductors crystallise to form the emissive component. Cao et al.[1] use relatively standard formamidinium lead iodide perovskite (FAPI) which they modify with an additive aminovaleric-acid (AVA) to control morphology. Lin et al.[2] introduce a new composite perovskite of methyl ammonium bromide (MABr) and $CsPbBr_3$ which creates a quasi-core-shell structure.

Achieving high EQEs in any LED requires non-radiative losses to be minimised, i.e. elimination of the electron-hole recombination pathways that do not produce a photon. Both PLED approaches appear to deliver on this imperative in equal measure. But this is where we come to a subtle distinguishing feature: Cao al.[1] target the well-known 'outcoupling-problem' of thin film LED structures (such as PLEDs and OLEDs). The optical physics of a planar diode mean that 70%-80% of the light generated by the semiconductor remains trapped in the device – obviously this leaves room for improvement. Various strategies have been employed to address the issue in OLEDs such as diffraction gratings and

buckling patterns. Cao et al.[1] take a simpler and more elegant approach by spontaneously structuring the emissive layer on the sub-micron scale through the formation of crystal platelets (**Figure 1**). The platelet formation is controlled by, and is sensitive to the processing conditions. Modelling shows that the sub-micron structuring increases the output coupling to 30% versus 22% for the equivalent 'flat-layer' perovskite device. This, in combination with the reduced non-radiative losses, delivers an EQE of 20.7% at 800 nm (near infra-red). In contrast, Lin et al.[2] stick with a 'flat' emissive layer and seek to further optimise the balance between electron and hole injection, i.e. make most efficient use of every charge. This is apparently facilitated by the MABr shell (of the quasi-core-shell structure). These PLEDs deliver 20.3% EQE at 525 nm (green).

Whist these EQEs are undoubtedly a major step forward in realising PLEDs with technologically useful efficiencies – caution is advised before ordering your 55" PLED-UHD-TV. OLEDs, and indeed all organic-semiconductor-based optoelectronics suffered for many years from stability issues. The first polymer OLEDs lasted seconds, but advances in encapsulation and light emitting materials mean that your smart phone screen or OLED TV will last 10s-of-thousands of hours. Following a similar trajectory, the PLEDs of Cao et al.[1] and Lin et al.[2] have modest T50s (time for the performance to drop by half) of 20 hours and 100 hours respectively. Furthermore, displays require a minimum of three colours (preferably more) to create a high quality colour image – this was a significant challenge for OLEDs, now largely overcome. The PLED of Cao et al.[1] has NIR emission, and Lin et al.[2] narrowband green emission. Definitely a start. Bandgap engineering via composition should deliver multiple colours of PLEDs, but the same journey as OLEDs lays ahead. Finally, these two papers highlight a perennial problem that reoccurs every time a new optoelectronic material platform emerges – inconsistency in characterisation and the lack of standards. Being outside the human eye spectral response band, Cao et al.[1] report their metrics radiometrically (for example radiance in $Wsr^{-1}m^{-2}$), but Wei et al.[2] photometrically (luminance in cdm^{-2}). The photometric measure is weighted by the response of the human eye, the radiometric measure simply the emitted power per unit solid angle and projected area. In addition, peak EQEs are reported under different brightnesses and hence drive currents. This all makes direct comparison somewhat problematic. These caveats aside, both papers are a significant milestone in PLED development. However, compound semiconductor LEDs remain by far the dominant technology – in terms of cost, efficiency, colour and brightness, available wavelengths and compatibility with phosphors for white lighting. They will be hard to beat but that should not stop the perovskite or indeed organic pioneers!

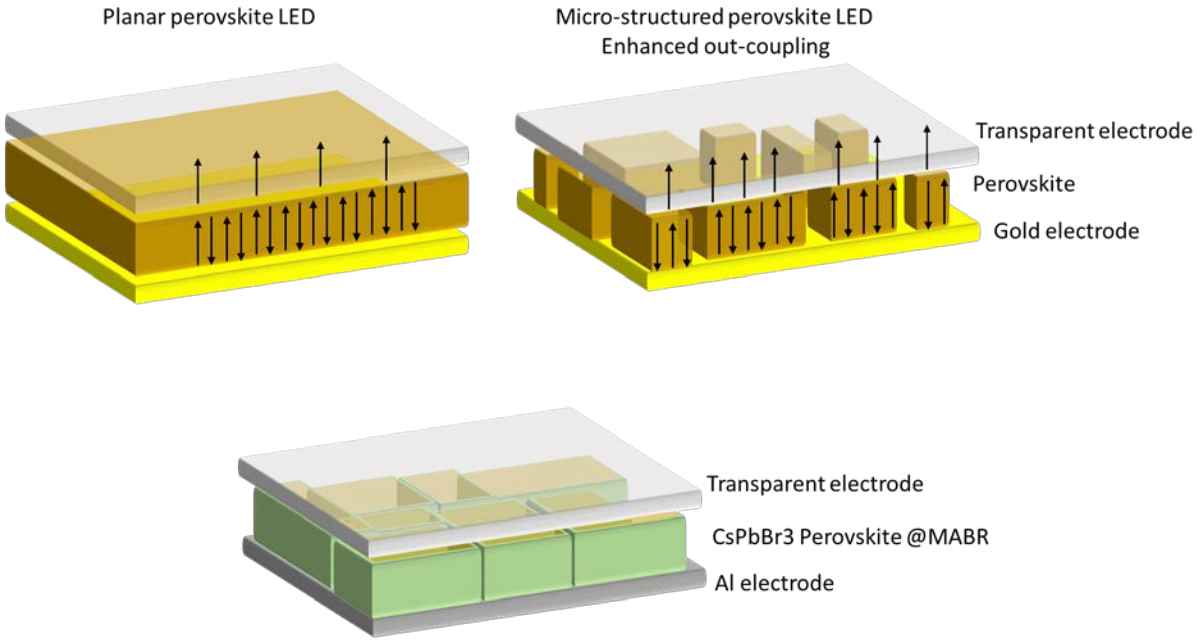

Figure 1 | Improved light-emitting diodes (LEDs) based on perovskite semiconductors. a, LEDs have previously been made from perovskites by sandwiching a thin layer of the semiconductor between a gold electrode and a transparent electrode. However, only about 20% of the light generated in the perovskite escapes from the device. b, Cao et al. report perovskite LEDs (PLEDs) in which the semiconductor layer consists of separated submicrometre-sized crystals, partitioned from the gold electrode by a thin layer of an organic material. This design increases the amount of light that escapes. c, Lin et al.2 report PLEDs based on a different perovskite, in which the semiconductor crystals are partly enclosed by an organic compound and the gold electrode is replaced by an aluminium one. This device optimizes the efficiency with which charges (not shown) that are pumped into the perovskite are converted into photons.

References

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