Bright, efficient and stable LEDs made using nanocrystals of perovskite material

Perovskites are promising candidates for use in next-generation light-emitting diode (LED) displays that are vivid and have high colour quality. LEDs made from particles with a perovskite nanocrystal core and an acidic shell are efficient and bright, and have a long operational half-life.

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The problem

Most people rely heavily on vision, and so display screens have a crucial role in disseminating information in today's world. Manufacturers are keen to develop vivid display screens that convey reality faithfully. Ionic materials called metal halide perovskites (MHPs) can emit vivid light with very pure colours. As such, they are promising candidates for use in next-generation light-emitting diode (LED) displays that could overcome the colour-quality limitations of current commercial LEDs made with organic materials[1].

Perovskite LEDs (PeLEDs) have been developed containing films of MHPs in the form of relatively large polycrystalline grains or colloidal nanocrystals. However, charge movement is poorly confined in polycrystalline MHP grains, leading to low PeLED efficiency. Colloidal MHP nanocrystals need to be synthesized with insulating ligand molecules, which impede their ability to transport charge from electrodes, and decrease operational stability and brightness[2–4]. The trade-off between charge confinement and charge transport has limited the development of PeLEDs that are simultaneously efficient, bright and stable enough for commercial use[5].

The solution

We explored ways to confine charges in MHP particles while maintaining their excellent charge-transport properties. Our solution was to encapsulate a nanoscale perovskite crystal core in a shell made of the small acidic molecule BPA to create a 'core/shell' structure as the MHP film formed. Adding BPA to bulk MHP crystals resulted in self-assembly of BPA molecules on the MHP surface to generate what we call in situ particles. With sufficient reaction with BPA, the large grains of MHP split into nanocrystals about 10 nanometres in diameter that were surrounded by BPA molecules to form the in situ core/shell structure. We used high-resolution techniques to directly image the behaviour of the MHP crystal as it split into nanocrystals to form the core/shell structure. We assessed the photoluminescence properties of the films and the electrical properties of the structures.

The core/shell structure showed strong charge confinement while retaining the excellent charge-transport property of bulk MHPs. The construction method avoids the need for long insulating molecules that have previously been used to synthesize colloidal MHP nanocrystals but that degrade charge transport. The PeLEDs that we developed with core/shell nanocrystals showed high peak efficiency: the ratio of the number of consumed electrons to the number of emitted photons was almost 28.9% (Fig. 1a). They also showed a maximum brightness of about 470,000 candela per square metre and an operating half-life of more than 30,000 hours at 100 candela per square metre (Fig. 1b). This is an unprecedented report of simultaneous high efficiency, high brightness and long lifetime in PeLEDs.

The implications

This work indicates that PeLEDs are not just laboratory-level devices, but are realistic candidates for commercial displays and lighting applications. We see it as an advance towards the development of vivid displays that can replicate natural colours accurately. We used our core/shell nanocrystals to make green-light-emitting PeLEDs that achieved brightness and efficiency comparable to those of state-of-the-art green LEDs made with semiconducting nanocrystals called quantum dots. Moreover, the operating voltage of our PeLEDs at 10,000 candela per square metre (2.7 volts) is lower than that for any other LED yet.

Drawbacks of PeLEDs include their high vulnerability to degradation by moisture, oxygen and heat, and to ion migration during operation. Therefore, the efficient, long-term operation of future PeLEDs might rely on moderate and low running temperatures, and on stable encapsulation of MHP materials to avoid ion migration.

Future work will aim to suppress the intrinsic instability of PeLEDs and elucidate their degradation mechanism. Current research is seeking to further optimize the core/shell structure and the structure of devices that use this material technology.

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EXPERT OPINION

"This manuscript reports the use of BPA to passivate perovskites by forming core/shell structures, resulting in highly efficient LEDs. The performance of the device is impressive, and the study seems to be a milestone contribution to the field of perovskite LEDs. The gains made in the stability of the material and the device under operation are particularly notable."

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FIGURE

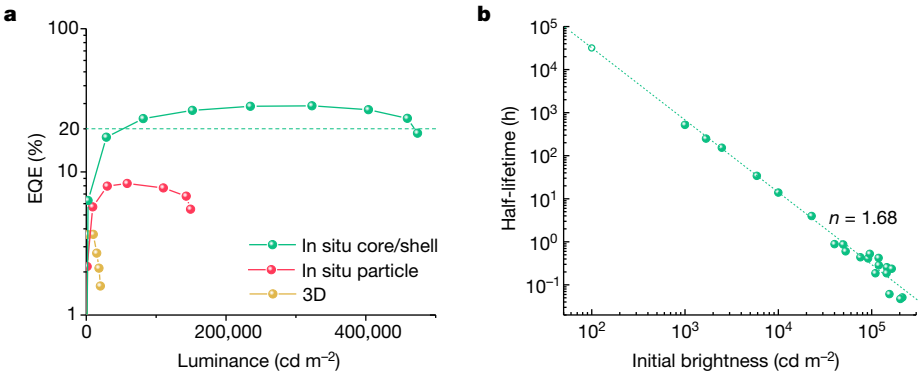

Figure 1 | The efficiency and half-lives of light-emitting diodes that contain an optimized form of perovskite material. Metal halide perovskites (MHPs) are promising materials for use in light-emitting diodes (LEDs). To optimize their form for this application, large grains of MHPs (3D) were treated with small molecules of an acid called BPA, which self-assembled on the MHP surface to create in situ particles. Treatment with sufficient BPA caused these particles to split into nanocrystals with MHP core and BPA shell (in situ core/shell). **a**, LEDs containing these forms of MHP were tested for their external quantum efficiency (EQE; a measure of the ratio of electrons consumed to photons emitted) at various brightnesses. **b**, The half-lifetimes of perovskite LEDs with in situ core/shell structures. n, acceleration factor for the accelerated half-life equation ($L^n \times T_{50}$ = constant, where L is initial brightness and T_{50} is half-life); cd m^{-2}, candela per square metre.

BEHIND THE PAPER

We have tried various strategies to make MHPs emit light efficiently. However, colloidal nanocrystals synthesized using excess alkyl ligand molecules showed poor charge transport; large particles formed without excess ligands showed insufficient charge confinement. This suggested that the ideal MHP emitter should have small crystals about 10 nanometres in diameter for efficient charge confinement, but that the ligands surrounding the nanocrystals should be short to enable efficient charge transport. Thus, we came up with the idea of splitting large MHP grains into nanocrystals during film formation, and simultaneously passivating (coating) internal and surface defects in the nanocrystals using short acidic ligands. Reacting the large crystals with BPA molecules led to the grains spontaneously splitting down to the target 10 nanometres, with concurrent surface passivation. This gave rise to the core/shell nanocrystal structure, which achieves fast charge transport and strong charge confinement for the efficient and stable emission of bright light in LEDs.

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FROM THE EDITOR

Perovskite materials are promising for LEDs, but it is difficult to combine efficiency, brightness and stability in a single device. This paper stood out to me because of the novelty of the fabrication process, as well as the impressive performance of the measured LEDs, which represents a record result for this field.

Christiana Varnava, Senior Editor, *Nature*