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RESEARCH HIGHLIGHTS

White light-emitting diodes from perovskites

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White light-emitting diodes (WLEDs), as key infrastructure, play an important role in the field of lighting and display. In the past few decades, many methods were developed to prepare WLEDs. A common strategy is to use blue LEDs to excite yttrium aluminum garnet (YAG) phosphors and generate composite white light, which is now the main technology for commercial lighting. In 2014, Nobel Prize in Physics was awarded to Nakamura *et al.* for their contribution to blue LEDs[1, 2]. However, the WLEDs made by the above strategy suffer from color instability, the high cost of rare-earth elements, and low color rendering index (CRI), making it hard to meet the requirements of high-quality lighting and display. The problem of low CRI can be solved by mixing different color emitters in a partial electroluminescence or full electroluminescence mode. WLEDs with mixed color emitters like organic molecules, cadmium-based quantum dots, and perovskites have been demonstrated[3–5]. However, the multi-emitters strategy still has obvious limitations. For example, mixing different emitters with a specific ratio leads to increased cost and fabrication difficulty. In addition, the mixing of multiple color emitters causes the decrease of device performance due to the self-absorption effect. Furthermore, the color rendering will change with the operating time, because different emitter has different luminescence stability.

To solve the issues of manufacturing cost, self-absorption effect, color instability, etc., utilizing a white light-emitting semiconductor, which can emit either multiple colors (red, green, and blue) or the entire visible-light spectrum, is a feasible strategy. Notably, recent research on LEDs reveals that perovskite emitters not only have narrow-band emission[6, 7], but also demonstrate multiple-color or broadband white-light emission[8–11]. Some outstanding works were published on white-light emission from perovskite emitters, providing a promising strategy for next-generation WLEDs.

Luo *et al.* studied the broadband white-light emission from the self-trapped excitons (STEs) in perovskite emitters ($Cs_2Ag_xNa_{1-x}InCl_6$) (Figs. 1(a)–1(c))[9, 12]. They found that alloying Na^+ into $Cs_2AgInCl_6$ can break the dark transition (parity-forbidden transition), realizing efficient and stable single-material white-light emission (400–800 nm, Fig. 1(b)). The photoluminescence quantum yield (PLQY) was improved from < 0.1% to the highest value of 86% (average value ~70%, Fig. 1(c)) via bismuth doping. However, owing to the large bandgap of $Cs_2Ag_xNa_{1-x}InCl_6$ and the confinement characteristics of STE, the exciton mobility is very low in the LEDs with $Cs_2Ag_xNa_{1-x}InCl_6$ emitters. The peak current efficiency of $Cs_2Ag_{0.6}Na_{0.4}InCl_6$-based WLED is only 0.11 cd A^{-1}.

Lead halide perovskite materials were also used for white-light electroluminescence. Sun *et al.* reported high-efficiency multiple-color-emitting Sm^{3+}-doped $CsPbCl_3$ perovskite quantum dots (Figs. 1(d)–1(g)), delivering a maximum PLQY of 85% (Fig. 1(f))[10]. Moreover, using the Sm^{3+}-doped $CsPbCl_3$ perovskite quantum dots as the active layer for LEDs, they successfully achieved co-electroluminescence from perovskite and Sm^{3+}. By adjusting the doping content of Sm^{3+}, a single-component WLED with a maximum brightness of 938 cd m^{-2}, an external quantum efficiency (EQE) of 1.20%, and a CRI of 93, was obtained (Figs. 1(d) and 1(g)).

$CsPbI_3$ is another popular perovskite material for optoelectronic devices. It is prone to make phase transition (from α-$CsPbI_3$ to δ-$CsPbI_3$), which is unwanted for solar cells. Chen *et al.* found that the phase transition of $CsPbI_3$ can be used to make WLEDs. They developed a method to control the phase transition[11]. α-$CsPbI_3$ and δ-$CsPbI_3$ were evenly distributed in a $CsPbI_3$ layer (Fig. 2(a)), presenting a synergistic photoelectric effect. The α-$CsPbI_3$, δ-$CsPbI_3$ and α-/δ-$CsPbI_3$ films show different charge carrier transport and recombination processes (Fig. 2(b)). α-$CsPbI_3$ has strong charge-transporting capacity, but δ-$CsPbI_3$ is poor in carrier injection due to the confinement characteristics of STE. However, when the two phases co-exist, α-$CsPbI_3$ can help δ-$CsPbI_3$ on carrier transport and injection under the electric field, enabling δ-$CsPbI_3$ to generate efficient electroluminescence with a broadband emission spectrum. The intrinsic red-light emission from α-$CsPbI_3$ can also supplement the broadband emission spectrum (Fig. 2(c)). Thanks to the synergistic effect of α-$CsPbI_3$ and δ-$CsPbI_3$, efficient and balanced carrier injection are realized at the heterogeneous interface, thus yielding the first high-performance perovskite WLED in the world. The WLED showed a brightness of >1000 cd cm^{-2} at a low voltage of 4.6 V (Fig. 2(d)). The maximum EQE and current efficiency reached 6.5% and 12.2 cd A^{-1}, respectively (Fig. 2(e)).

In summary, compared with the traditional materials with narrow-emission characteristics, perovskites can emit white light or multiple-color light, which enables to make WLEDs with a single emitter. Perovskite emitters have been successfully applied to LEDs in backlight mode and electroluminescence mode. Owing to the advantages of solution pro-

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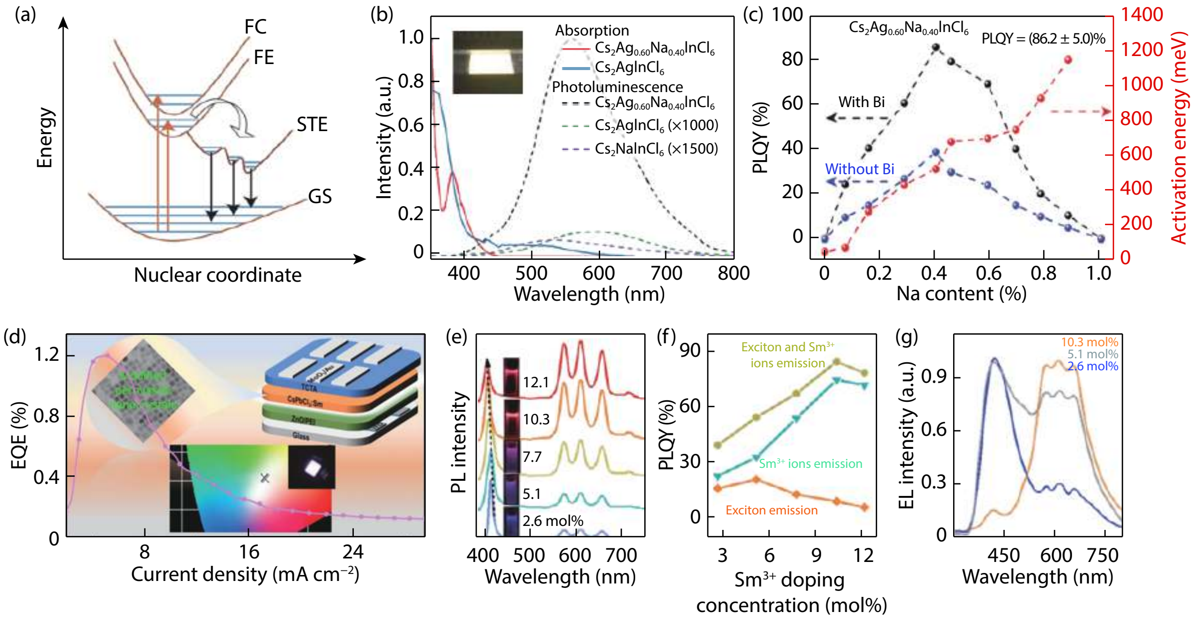

Fig. 1. (Color online) (a) A schematic illustration of STE emission. FC, free carrier state; FE, free exciton state; STE, self-trapped exciton state; GS, ground state. Reproduced with permission[12], Copyright 2020, Nature Publishing Group. (b) Absorption (solid lines) and photoluminescence (dashed lines) spectra for $Cs_2AgInCl_6$ and $Cs_2Ag_{0.60}Na_{0.40}InCl_6$. (c) Activation energy and PLQY of $Cs_2Ag_xNa_{1-x}InCl_6$ powder *vs* Na content. Reproduced with permission[9], Copyright 2018, Nature Publishing Group. (d) External quantum efficiency (EQE) of $CsPbCl_3$:Sm^{3+}-based WLED. The inserted pictures are the structure of the device, the transmission electron microscopy (TEM) image of Sm^{3+}-doped $CsPbCl_3$ perovskite quantum dots, and the photo of a working WLED. (e) Emission spectra of Sm^{3+}-doped $CsPbCl_3$ with different doping content under the excitation of 365 nm. (f) PLQYs as a function of Sm^{3+} doping content. (g) EL spectra for the LEDs based on Sm^{3+}-doped $CsPbCl_3$ with different doping content. (d)–(g), reproduced with permission[10], Copyright 2020, American Chemical Society.

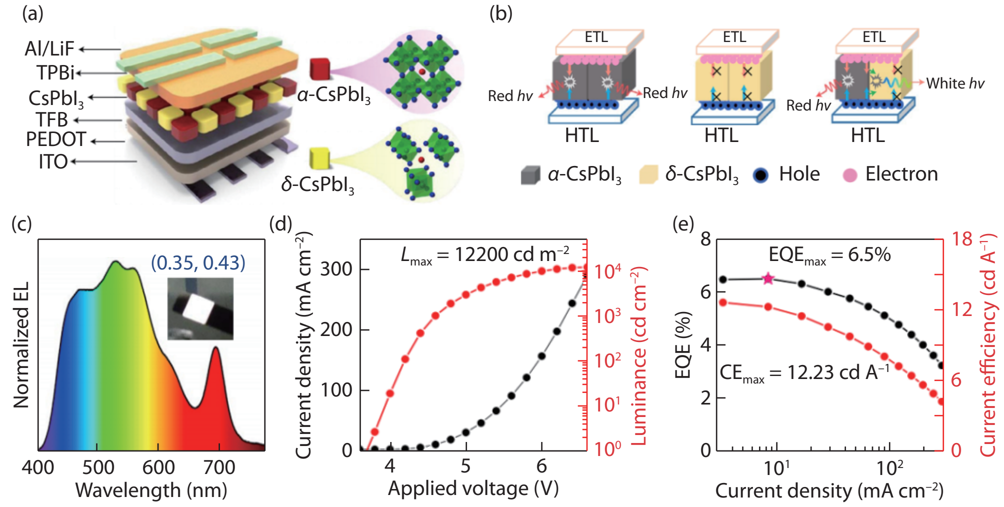

Fig. 2. (Color online) (a) Structure of the perovskite WLED with an active layer composed of α-$CsPbI_3$ and δ-$CsPbI_3$. (b) The carrier injection and recombination mechanism for the perovskite WLEDs. (c) Electroluminescence spectra. (d) Current density–voltage (*J*–*V*) curve and luminance–voltage (*L*–*V*) curve for the perovskite WLEDs. (e) External quantum efficiency and current efficiency of the WLEDs. Reproduced with permission[11], Copyright 2021, Nature Publishing Group.

cessing, abundance of raw materials, and excellent electroluminescence property, perovskite emitters are promising candidates for next-generation low-cost, low-power, and high-CRI WLEDs.

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