New pure-red perovskite LEDs combines high efficiency and brightness

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The advent of light-emitting diode (LED) technology transformed artificial lighting from a high-energy, low-efficiency thermal process into a precise, controllable, and energy-efficient optoelectronic system, ushering in a new era of low-power, long-lifetime, and high-quality illumination. However, as society advances and LEDs find increasing applications in cutting-edge fields such as displays, optical communications, and biomedical technologies, there is growing demand for higher performance in terms of quality, efficiency, intelligence, and integration. Conventional inorganic semiconductor materials now face limitations in addressing these demands, prompting the exploration of alternative technologies such as organic LEDs (OLEDs), quantum dot LEDs (QLEDs), and perovskite LEDs (PeLEDs).

While OLEDs and QLEDs have already entered the market, their high cost and low yield remain significant barriers to widespread adoption. In contrast, PeLEDs, despite having a development history of only about a decade, exhibit tremendous potential due to their low-cost and abundant raw materials, simple fabrication processes, continuously tunable emission spectra, narrow full width at half maximum (FWHM), and high photoluminescence quantum yields. The excellent solution processability of metal halide perovskites further enhances their appeal, making them particularly suitable for scalable manufacturing of high-performance optoelectronic devices through advanced printing techniques.[1] These combined merits have driven rapid progress in PeLED performance, with device efficiencies advancing at an unprecedented pace. Notably, PeLEDs have progressed rapidly, and within ten years, their external quantum efficiencies (EQEs) have nearly matched those of OLEDs, with green, red, and near-infrared PeLEDs already achieving efficiencies around 30%.

Besides the efficiency, color purity plays a vital role in full-color display technologies, as it directly affects color saturation, accuracy, and overall visual performance.[2] To achieve a wide color gamut and precise color rendering, the red, green, and blue emitters must exhibit narrow emission spectra and high chromatic purity. Low color purity results in spectral overlap, color distortion, and degraded image contrast. This is particularly critical for advanced display applications such as augmented reality, virtual reality, medical imaging, and microdisplays, where visual fidelity is essential. Among the three primary colors, achieving high-performance pure-red emission remains especially challenging. While significant progress has been made in developing pure-red LEDs using quantum dots and organic semiconductors, these often suffer from stability issues or low efficiency. Recently, pure-red PeLEDs have emerged as promising candidates due to their narrow FWHM and high luminance potential, offering a path toward high-performance full-color display.

Although pure-red PeLEDs with EQEs exceeding 20% have been demonstrated using low-dimensional or quantum dot perovskite materials,[3,4] these materials typically exhibit lower charge carrier mobilities compared to bulk 3D perovskites, making it difficult to

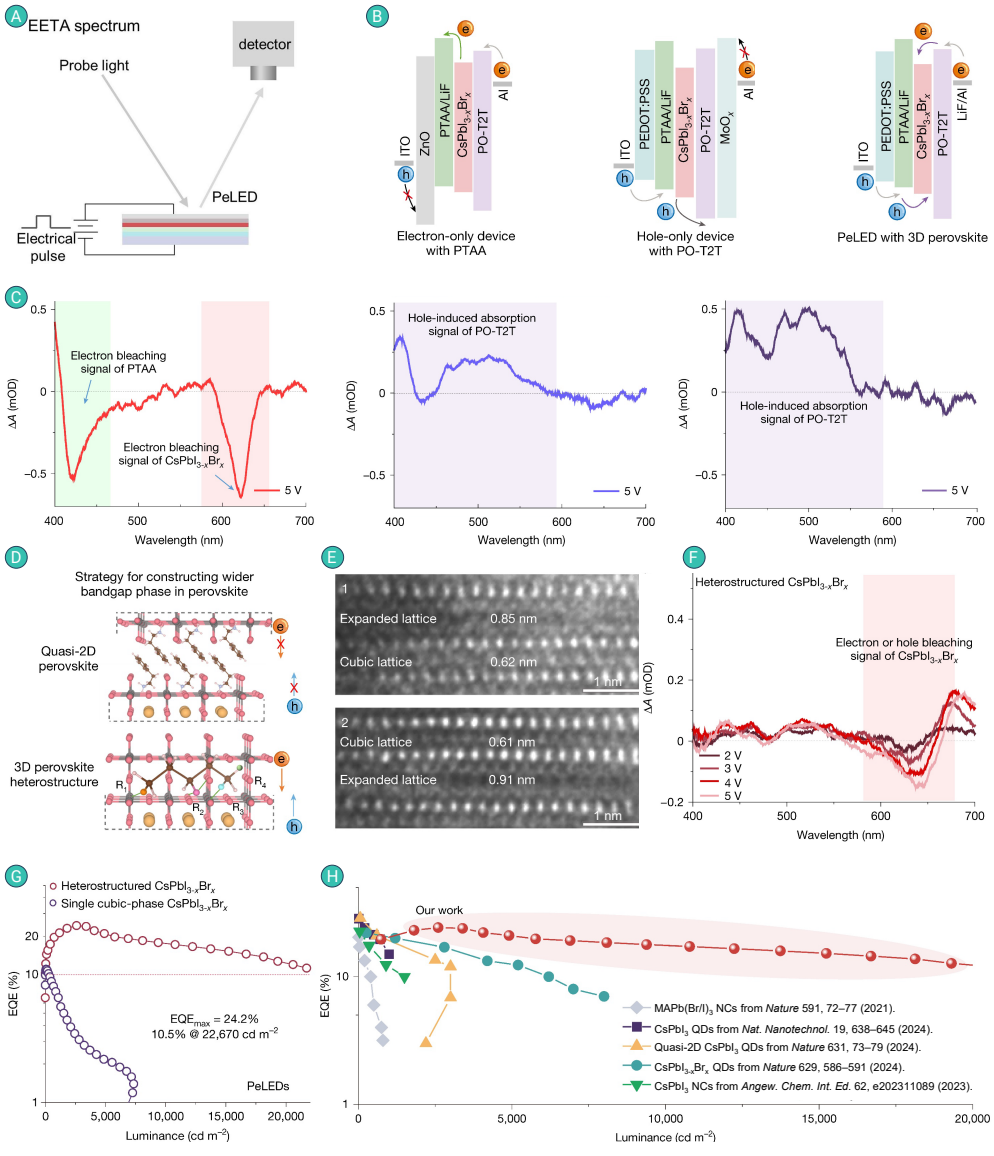

Figure 1. Intragrain 3D perovskite heterostructure for high-performance pure-red perovskite LEDs (A) Schematic diagram of EETA spectroscopy. (B) Schematic illustration of the device structures and (C)EETA spectra of the electron-only (left), hole-only (middle) devices, and full PeLED devices (right). (D) Comparison of strategies for constructing a wider bandgap phase in perovskite. (E) Magnified atomic-resolution aberration-corrected HAADF-STEM image of the heterostructured $CsPbI_{3-x}Br_x$ grain. (F) EETA spectra of PeLEDs based on the heterostructured film. (G) EQE-luminance relationship for the fabricated PeLEDs. (H) Summary of the reported EQE-luminance of representative pure-red PeLEDs. (Reproduced with permission.[5] Copyright 2025, Springer Nature)

simultaneously achieve high brightness and high efficiency. In theory, bulk 3D halide-mixed perovskites such as $CsPbI_{3-x}Br_x$ possess higher carrier mobilities and hold great promise for realizing pure-red PeLEDs with both high efficiency and high brightness. However, PeLEDs based on these materials often suffer from severe efficiency roll-off at high brightness, preventing them from maintaining high efficiency under strong electrical excitation. Moreover, the fundamental cause of the efficiency roll - off in PeLEDs is still not well - defined.

To address this issue, Song et al.[5] developed an electrically excited transient absorption (EETA) spectroscopy technique. As illustrated in Figure 1A, by applying pulsed current to the device while recording the transient absorption spectra, the electronic states of electrons and holes in various functional layers can be monitored in situ. To better understand carrier dynamics, the authors designed single-electron and single-hole devices for comparison with the standard device. Figure 1B shows the architectures of these three device types along with their respective EETA spectra (Figure 1C). The results revealed an electron bleaching signal in the perovskite and hole transport layers of the single-electron device, and a hole-induced absorption signal in the electron transport layer (ETL) of both the single-hole and standard devices. Hole leakage may occur due to imbalanced charge carrier transport, leading to hole accumulation at the perovskite/ETL interface. These accumulated holes can then migrate into the ETL via defect-assisted tunneling. These findings indicate that, during operation, holes can leak across the emissive perovskite layer into the electron transport layer, which is the primary cause of the significant efficiency roll-off observed in pristine $CsPbI_{3-x}Br_x$ PeLEDs at high brightness.

Building on the successful design strategies of all-inorganic quantum well LEDs and QLEDs, Song et al.[5] proposed that enhancing carrier confinement by epitaxially growing larger bandgap barriers could effectively reduce hole leakage. However, conventional bulky organic cations, such as a phenylethylamine cation, while capable of increasing the bandgap, often disrupt the crystal structure of bulk 3D perovskites, leading to reduced carrier mobility. To overcome this limitation, the authors introduced p-toluenesulfonyl-LAG (PTLA), a molecule with multiple anchoring groups, as an intercalation agent. This molecule expands the lattice without compromising the integrity of the $[PbX_6]^{4-}$ framework. As illustrated in Figure 1D, traditional bulky cation intercalation tends to form quasi-2D perovskite phases, which negatively affect carrier mobility. In contrast, PTLA enables the formation of heterostructured 3D perovskites that retain the desirable transport characteristics of the bulk material. High-resolution high-angle annular dark-field scanning TEM (HAADF-STEM) imaging (Figure 1E) further confirms that PTLA can be successfully incorporated into the lattice without disrupting the original 3D perovskite structure. Moreover, EETA spectroscopy (Figure 1F) performed on PTLA-intercalated PeLEDs reveals the elimination of the hole-induced absorption signal in the electron transport layer, indicating that hole leakage is effectively suppressed through this strategy.

To evaluate the effectiveness of this heterostructure engineering approach, Song et al.[5] fabricated PeLED devices with identical architectures but with and without the PTLA-induced heterostructured $CsPbI_{3-x}Br_x$ active layer. As shown in Figure 1G, devices incorporating the heterostructured perovskite exhibited significantly reduced efficiency roll-off, achieving a peak EQE of 24.2% and maintaining an EQE of 10.5% at a high luminance of 22,670 cd m^{-2}. A comparison with previously reported pure-red PeLEDs (Figure 1H) further demonstrates that this strategy effectively enables the realization of devices with both high efficiency and high brightness, addressing a long-standing challenge in the development of pure-red PeLEDs.

In summary, Song et al.[5] developed an in-situ EETA spectroscopy technique to monitor electron and hole transport dynamics during PeLEDs operation, revealing significant hole leakage in conventional 3D perovskite-based pure-red PeLEDs. This methodology establishes a novel platform for probing microscopic carrier behaviors in operational LEDs and provides critical insights into failure mechanism analysis. Furthermore, the authors engineered 3D perovskite heterojunctions to suppress hole leakage, effectively mitigating efficiency roll-off and achieving high-efficiency pure-red PeLEDs at high brightness. This development underscores the significant potential of PeLEDs for applications in full-color displays and next-generation lighting technologies. Although operational stability requires further optimization to meet commercialization standards, continued advancements in device stability are expected to establish PeLEDs as competitive candidates for future optoelectronic applications.

The operational stability of PeLEDs remains fundamentally constrained by several primary mechanisms: ion migration, defect-mediated recombination, Auger recombination, thermal degradation, and interfacial reactions. To address these challenges, global research teams have developed multifaceted solutions spanning material engineering, device optimization, and process innovation, significantly advancing the practical deployment of PeLED technology. Specifically, in the field of pure-red PeLEDs, researchers have significantly optimized the phase stability of perovskite by regulating epitaxial heterojunction interfacial stress and designing intragrain heterostructures. Simultaneously, the implementation of defect passivation strategies and crystallization kinetics control techniques has effectively reduced defect density and enhanced crystal quality. These innovative approaches have enabled a breakthrough in operational lifetime for pure-red PeLEDs, extending from minute-level to hundred-hour-scale stability. Nevertheless, substantial barriers persist in the commercialization of this technology, which can be primarily attributed to four critical challenges: (1) persistent water/oxygen sensitivity and inadequate packaging solutions; (2) inevitable efficiency roll-off and carrier leakage under high-brightness operation conditions; (3) ongoing toxicity concerns associated with lead content and the significant performance deficiencies of lead-free alternatives; and (4) challenges in achieving scalable production. Interdisciplinary research efforts focusing on carrier dynamics optimization, defect engineering advancements, and large-scale manufacturing innovations are anticipated to significantly accelerate the industrialization trajectory of this technology.

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DECLARATION OF INTERESTS

The authors declare no competing interests.