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COMMENTARY

Green InP-based quantum dot light-emitting diodes made efficient and stable

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The 2023 Nobel Prize in Chemistry was awarded to Moungi G. Bawendi, Louis E. Brus and Alexei Ekimov for their discovery and synthesis of quantum dots (QDs). QDs are at the core of modern nanoscience and nanotechnology. The exceptional luminescent properties of these materials are particularly well suited for display and lighting technologies, among which QD-based light-emitting diodes (QLEDs) have been envisioned as the ultimate display technology due to their high efficiency, low cost and unmatched color purity. Over nearly three decades of dedicated research, scientists have significantly improved the external quantum efficiency (EQE) and stability of red, green, and blue QLEDs. However, most of these impressive advancements have been achieved with CdSe-based devices, whereas environmentally friendly cadmium-free QLEDs, which comply with safety regulations for consumer devices, still exhibit relatively lower performance. In principle, InP QDs provide a non-toxic and efficient alternative to cadmium-based QDs. They offer high photoluminescence quantum yield (PLQY), tunable emissions, and compatibility with existing technologies, making them highly suitable for sustainable display and lighting applications.[1]

In 2019, Won et al. developed a synthesis method for uniform InP cores and symmetrical InP/ZnSe/ZnS QDs, achieving a PLQY of nearly 100%.[2] This advancement significantly reduced energy transfer losses and Auger recombination. The optimized red QLEDs exhibited a maximum EQE of 21.4%, peak luminance of 100,000 cd m^{-2}, and an impressive operational lifetime of 1 million hours at 100 cd m^{-2}, making them comparable to Cd-based QLEDs. However, green QLEDs based on InP QDs still suffer from a relatively low EQE (16.3%) and a short operational lifetime (T_{95}@1,000 cd m^{-2} < 10 h), posing a critical challenge for the development of full-color Cd-free QLED-based display and lighting applications.

Elucidating the fundamental origins of the low efficiency and short operational lifetimes of green InP-based QLEDs is crucial for enhancing their performance. Recently, Shen's group at Henan University achieved a significant breakthrough in both efficiency and operational lifetime for devices emitting at 543 nm by optimizing the electronic structure of green InP-based core/shell QDs. The results have been published in a recent issue of Nature.[3] The study represents an important milestone in the development of QLEDs,

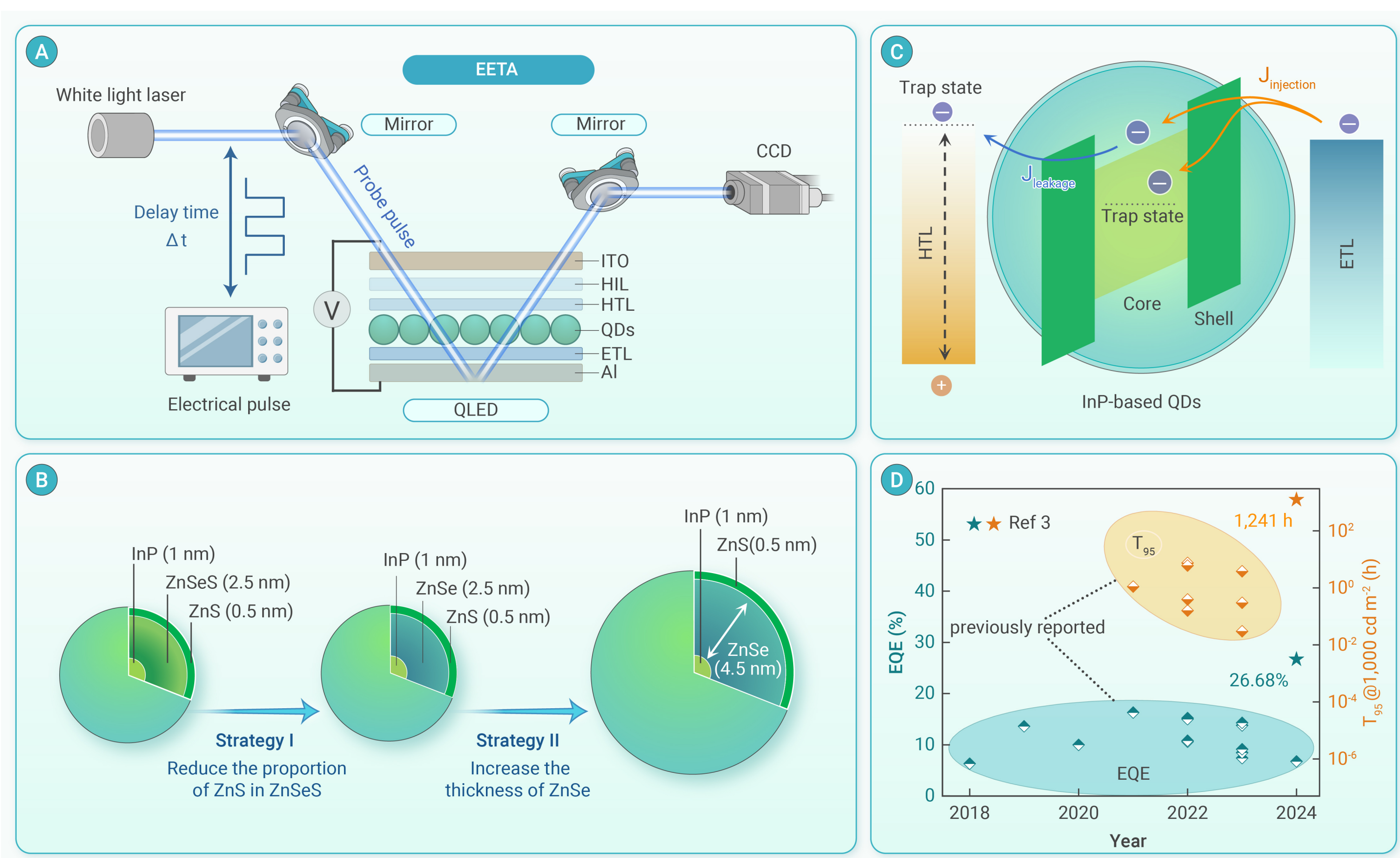

Figure 1. Electrically excited transient absorption (EETA) and a strategy for enhancing green InP-based QLEDs (A) Schematic diagrams of EETA. (B) Strategies to enhance the electron concentration of green InP-based QLEDs. (C) Schematic representation of electron injection and leakage in QLEDs according to the WKB model. (D) Comparing EQE and T_{95}@1,000 cd m^{-2} lifetime with previously reported values.

alongside several other notable studies published over the past decade.[2,4]

A critical enabler of this breakthrough is their newly developed electrically excited transient absorption (EETA) spectroscopy, which essentially replaces the optical pump pulses used in conventional transient absorption spectroscopy with electric pulses. This makes it particularly powerful for studying electrically driven devices such as LEDs (Figure 1A). This technique allows them to directly quantify the concentration of carriers accumulated in the QD emitting-layer and even in the charge transport layers. Consequently, they identified the primary failure mechanism of widely studied green InP-based QLEDs as low accumulated electron concentration. According to the conventional ABC model for inorganic LEDs, maintaining a higher electron concentration below the Auger recombination threshold helps minimize losses caused by trap-captured electrons, thereby achieving higher radiative quantum efficiency. However, the prevalent use of InP/ZnSeS/ZnS core/shell/shell structures in green cadmium-free QLEDs is complicated by the high injection barrier imposed by the ZnSeS interlayer. This barrier restricts electron concentration and trap saturation, eventually leading to low efficiency and short operational lifetime.

On the basis of this understanding, they chemically developed a new type of core-shell QDs with an unconventionally thickened ZnSe interlayer to replace the current best performing ZnSeS interlayer shell (Figure 1B). Specifically, they first replaced the ZnSeS interlayer with a ZnSe shell, which reduces the electron injection barrier, allowing more electrons to enter the QDs and thereby enhancing radiative recombination efficiency. However, this modification also increases electron leakage into the hole transport layer (HTL), introducing an additional challenge to the overall device performance. To mitigate this issue, the authors further thickened the ZnSe layer, effectively suppressing electron leakage without significantly hindering electron injection.

This strategy can be understood using the WKB quantum tunneling model (Figure 1C).[5] Due to the small energy barrier between the InP-based QD layer and the electron transport layer (ETL), a small change in the barrier height will significantly increase the amount of electron injection, thereby compensating for the reduction in electron injection caused by the increased thickness. On the other hand, due to the high energy barrier between the QD layer and the HTL, increasing the barrier thickness significantly reduces the probability of leakage tunneling, and ultimately, effective electron blocking can be achieved even at low energy barriers. This strategy enables them to achieve the unprecedented EQE of 26.68% and an extremely long operational lifetime (T_{95}@1,000 cd m^{-2}) of 1,240 h (Figure 1D), which exceeds the previous best values by a factor of 1.6 and 165, respectively, which demonstrates the first efficient and stable green InP-based QLED suitable for practical display applications.

To summarize, the advancements presented in this paper establish InP-based QLEDs as a viable replacement for Cd-based devices, paving the way for environmentally friendly, high-performance display and lighting technologies. Insights gained from this paper, particularly in balancing electron injection and leakage through shell structure engineering, can further drive the development of InP-based QLEDs with narrow emission, high efficiency and long lifetime. Although red and green Cd-free QLEDs have been progressing rapidly, their blue counterparts still lag behind Cd-based devices. The next significant milestone—achieving stable and efficient Cd-free blue QLEDs—is within reach by systematically investigating carrier injection and transport dynamics in blue devices using EETA spectroscopy. This approach will provide clear and precise engineering guidance for optimizing materials and device architectures.

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DECLARATION OF INTERESTS

The authors declare no competing interests.