# Efficient Pixelated Blue Quantum-Dot Light-Emitting Diodes via Direct Photo-Patterning

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## ABSTRACT

***In this work, we enhanced the efficiency of patterned blue quantum dot light-emitting diodes (QLEDs) by optimizing the ligand stability of the quantum dots. After photosensitive ligand exchange, the quantum dots maintained a high photoluminescence quantum yield (PLQY), ensuring strong emission properties. Following the lithography process, the device's external quantum efficiency (EQE) reached 14.5%. This demonstrates that through effective quantum dot and ligand optimization, high device performance can be achieved, even after complex fabrication steps such as lithography.***

## Author Keywords

Blue QDs; Ligand stability; Lithography; EQE; Blue QLED;

## 1 Introduction

Quantum dot light-emitting diodes (QLEDs) have garnered significant attention in recent years, particularly for their potential in high-performance displays. Known for their excellent color purity and narrow emission spectra, quantum dots (QDs) offer vibrant, lifelike colors. Their inorganic structure provides exceptional thermal stability, enabling longer device lifetimes even under high-brightness conditions. QLEDs can cover a wide color gamut, efficiently emitting light from deep blue to infrared, while maintaining low power consumption. With their combination of high efficiency, durability, and cost-effectiveness, QLEDs are increasingly viewed as a key player in the evolution of display technology.[1-5]

Quantum dots are widely used in the display industry, where pixel patterning is a critical step in device fabrication. Patterning processes for quantum dots include inkjet printing, transfer printing, and photolithography. Among these, photolithography has the advantage of overcoming the limitations of inkjet printing, such as low resolution, and the challenges of transfer printing, which can be difficult to apply to large-area displays. Photolithography enables high-resolution patterning, making it a highly suitable process for advanced quantum dot-based displays. However, despite these advantages, achieving high efficiency in blue QLEDs, especially after the lithography process, remains a significant challenge. Currently, the highest external quantum efficiency (EQE) reported for blue QLEDs post-lithography is around 12%, which lags behind the efficiency of QLEDs emitting in the red and green light regions.[6-9] A key issue is the significant reduction in the PLQY of quantum dots during the photolithography process. This decline in PLQY is mainly due to the introduction of surface defects during fabrication, which leads to increased non-radiative recombination. Surface defects act as trap sites for charge carriers, reducing the radiative recombination efficiency and thus lowering the overall light output of the device. The decrease in PLQY directly impacts the device's EQE, particularly at higher brightness levels, where the thermal and operational stability of the device is further strained. As the efficiency drops, the thermal energy generated in the device can accelerate degradation, further complicating efforts to maintain performance under operational conditions. Consequently, addressing the issue of PLQY degradation during lithography is essential for improving the efficiency and stability of blue QLEDs.[6]

In this work, we focus on enhancing the stability of quantum dot ligands to tackle these issues. By refining the ligand exchange process, we were able to maintain a PLQY of over 90% after photosensitive ligand exchange, ensuring that the optical properties of the QDs remain intact throughout fabrication. As a result, the blue QLED devices achieved an EQE of 14.5%, setting a new benchmark for devices produced using lithography. This improvement highlights the potential of material optimizations to push the boundaries of blue QLED efficiency and stability.

## 2 Results and discussion

Blue quantum dots typically consist of a ternary CdZnSe core, with an epitaxially grown shell to passivate surface defects (Figure 1). In this work, we built upon the conventional quantum dot structure by employing a facet-induced growth method, which increased the proportion of strongly coordinating ligands, such as native oleic acid. This strategy enhances the process stability of the quantum dots, providing improved resistance to degradation during fabrication and handling. The increased coordination between ligands and quantum dot surfaces helps maintain the optical and structural integrity of the quantum dots, making them more suitable for advanced device applications.

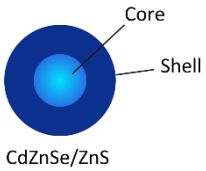


**Figure 1. Core-shell structure of QDs**

Initially, we synthesized blue quantum dots based on a CdZnSe core, with an emission peak centered at 465 nm, aligning well with the REC.2020 blue color gamut standard. Transmission electron microscopy (TEM) images confirmed that the quantum dots exhibited excellent monodispersity, which is crucial for achieving their narrow full-width at half maximum (FWHM) emission spectrum (Figure 2).

To further enhance their optical properties and minimize surface defects, the quantum dots were encapsulated with a wide-bandgap ZnS shell. This structural optimization was evident in the absorption spectra, where a sharp absorption edge in 300-400 nm was observed, indicating effective surface passivation. The pre-synthesized quantum dots demonstrated a photoluminescence quantum yield (PLQY) exceeding 90%, reflecting their high emission efficiency. These well-engineered quantum dots not only display excellent luminescence characteristics but also provide a stable platform for further integration into patterning process and device fabrication.


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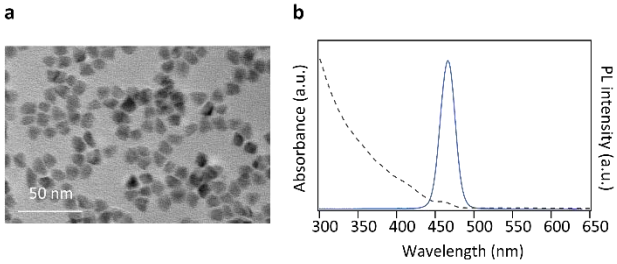


**Figure 2. (a) Transmission electron microscopy (TEM) image of as-synthesized QDs, (b) PL spectrum (solid line) and absorption spectrum (dashed line) of QDs.**

Subsequently, we carried out a ligand exchange on the quantum dots, using ligands containing photosensitive groups capable of crosslinking under UV exposure. The native oleic acid ligands were partially replaced in the presence of an excess of photosensitive ligands. This modification not only allowed the quantum dots to be dispersed in the green solvent PGMWA, which is compatible with production line processes (Figure 3), but also improved their processability. We characterized the optical properties of the quantum dots after ligand exchange, and the results indicated that the process had no significant negative impact on the PLQY. Time-resolved photoluminescence (TRPL) measurements showed that the quantum dots exhibited nearly single-exponential decay, demonstrating excellent photoluminescent properties. These results provide a strong foundation for the fabrication of high-efficiency devices in subsequent steps.

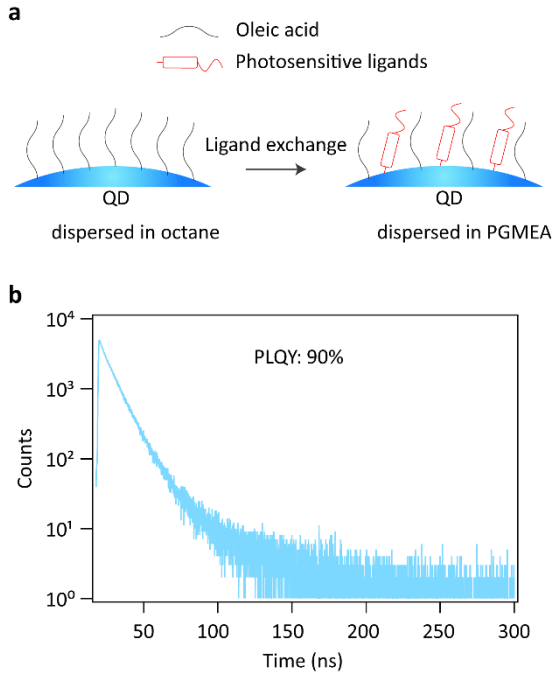


**Figure 3. (a) Schematic diagram of photosensitive ligand exchange process, (b) Time- resolved photoluminescence (TRPL) decay curves corresponding of QDs solution after ligand exchange.**

After ligand exchange, we validated the photolithographic patterning process. As shown in Figure 4a, we used 254 nm single-wavelength ultraviolet light to expose the quantum dot thin film after film formation. In the exposed areas under the mask, the quantum dot ligands undergo crosslinking, while in the unexposed regions, the ligands remain unchanged, preserving their solvent dispersibility. After PGMEA development, quantum dots in the exposed areas remain on the substrate, while those in the unexposed areas are washed away. We performed micro-fluorescence characterization of the patterned quantum dot film, with pixel regions measuring 5 ×39 μm. The fluorescence is uniform within the pixel areas, and there is almost no residual quantum dot in the non-pixel regions (Figure 4b).

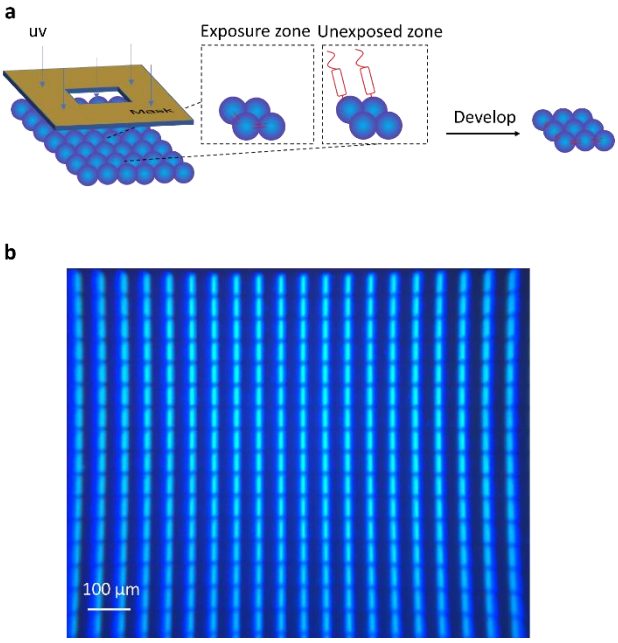


**Figure 4. (a) Schematic diagram of pattering process, (b) Microscopy image of patterned QDs film with ultraviolet excitation.**

The electroluminescent device was fabricated using a widely adopted bottom-emission structure with the configuration of ITO/PEDOT:PSS/TFB/patterned blue QDs/ZnMgO/Al. The energy band schematic diagram is shown in Figure 5b, with the quantum dot energy levels determined by ultraviolet photoelectron spectroscopy (UPS). The threshold voltage of the device at 1 cd $m^{-2}$ was measured at 2.7 V, which corresponds well to the quantum dot bandgap. The emission layer underwent a photolithographic patterning process, where the quantum dots, dispersed in PGMEA after photosensitive ligand exchange, were spin-coated onto the TFB layer. This was followed by UV exposure and development to define the patterned structure. The device exhibited low leakage current, indicating no significant charge leakage pathways were introduced during fabrication, preserving efficient charge transport (Figure 5c). The maximum luminance of the device exceeded 40,000 nits, demonstrating excellent brightness performance. The external quantum efficiency (EQE) peaked at 14.5%, with a corresponding current efficiency of 9.5 cd/A, setting a new benchmark for blue QLEDs fabricated using photolithography. These results underscore the effectiveness of the lithographic process in achieving both high efficiency and precise pixel patterning in device architecture (Figure 5d).

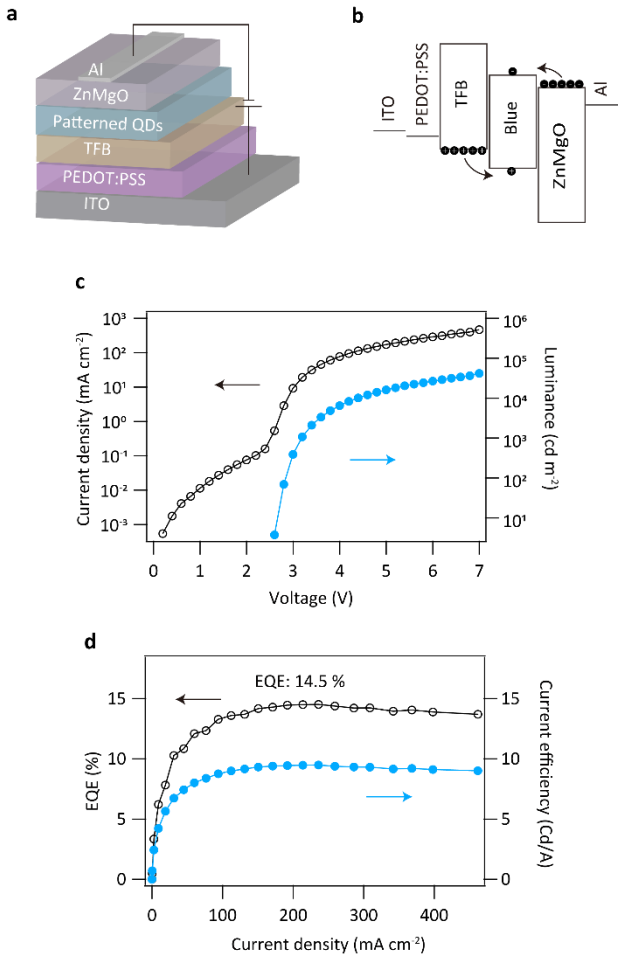


**Figure 5. (a) Schematic diagram of device structure, (b) Energy level of the devices, (c) Voltage-dependent current density (left axis) and luminance (right axis). (d) Current-dependent EQE (left axis) and current efficiency (right axis).**

## 3 Conclusion

In this study, we successfully developed blue quantum dots with enhanced ligand stability, which significantly improved their processability while preserving a high PLQY throughout the patterning process. The ligand exchange, which involved replacing native oleic acid ligands with photosensitive ones, allowed the quantum dots to remain highly dispersible in solvent while maintaining excellent optical properties. The photolithographic patterning process was successfully applied, with the quantum dots forming well-defined structures that exhibited uniform fluorescence across the pixel areas. The resulting electroluminescent device, fabricated using these quantum dots, achieved an impressive external quantum efficiency (EQE) of 14.5%, setting a new record for blue QLEDs after photolithographic processing. This work highlights the potential of these stable quantum dots to maintain their optical efficiency during processing, enabling high-performance devices suitable for scalable optoelectronic applications. The combination of enhanced quantum dot stability and efficient patterning demonstrates a promising pathway for advancing blue QLED technology.

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