Nanorod On-Chip LEDs for Display Backlights: Towards 200 Lumen per Watt Efficiency with Polarized Emission

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1. Introduction

Efficient white light-emitting diodes (LEDs) with an efficacy of 200 lm W−1 are much desirable for lighting and displays. The phosphor-based LEDs in use today for display applications offer poor color saturation. Intensive efforts have been made to replace the phosphor with quantum-dot-based downconverters, but the efficiency and stability of these devices are still in their infancy. Quantum rods (QRs), nanoparticles with an elongated shape, show superior properties such as relatively larger Stokes shifts, polarized emission, and high light out-coupling efficiency in the solid-state. However, these QRs usually suffer from poor optical quality for PL wavelengths < 550 nm. Herein, a gradient alloyed $CdSe/Zn_xCd_{1-x}S/ZnS$ and CdSe/CdS/ZnS core/shell/shell QR downconverters showing high efficacy LEDs covering a wide color gamut are reported. These QRs show high stability and a precisely tunable photo luminescence peak. The engineered shell thickness suppresses energy transfer and thus maintains the high quantum yield in the solid-state (81%). These QR-based LEDs attain an efficacy of 149 lm W−1 (@10mA) and wide color gamut (118% NTSC), which is exceedingly higher than state-of-the-art quantum dots and phosphor-based on-chip LEDs.

2. Results and Discussion

For the optimal color gamut and luminous efficacy of LCD, green and red QRs with 527 and 624 nm were selected (**Figure 1**), and a blue LED with 450 nm was used as pumping source. The two QRs were mixed uniformly with silicone and pasted onto the blue LED with a glue dispenser). By varying the mass ratio of these two QRs, one can manipulate the correlated color temperature (CCT) accordingly. The measured efficacy for the quantum-rod white LEDs (QRWLEDs) is 149 lm W−1 at 10 mA, which is significantly higher than the typical phosphors on the same blue LEDs (i.e., ≈80 lm W−1). Though the efficacy of QRWLED drops to 120 lm W−1 for the higher intensity at the higher current (50 mA), it is significantly higher than the phosphor-based LEDs (≈50 lm W−1). This highlights the excellent stability for the designed QRs under high luminous flux and high temperature. Later, we used these LED to build the LCD backlight and deployed to the LCD.

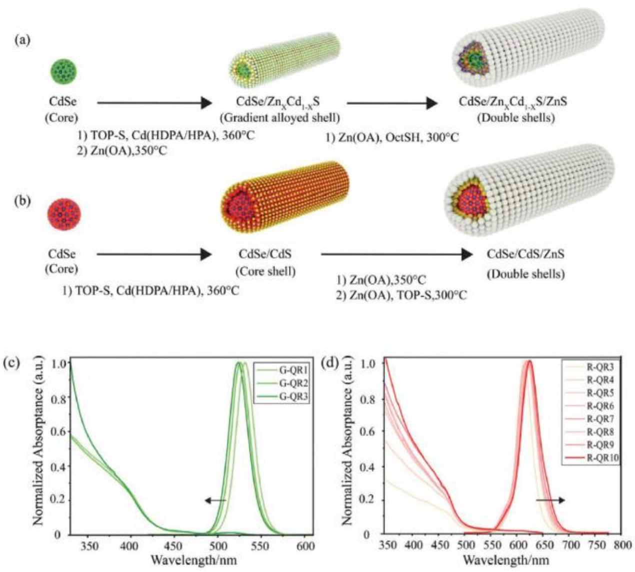

Figure. 1. a,b) Schematic of syntheses of the ZnS modified green (a) and red (b) QRs (TOP-S (trioctylphosphinesulfide), HDPA (hexadecy lphosphonate), HPA (hexylphosphonate), OA (oleate, oleic acid), OctS H (1-octylthiol)). c,d) UV–vis absorption and PL emission of green (G-QRs) (c) and red (R-QRs) (d) quantum rods in solution with incr eased shell composition.

We synthesized a series of green and red QRs with the configuration CdSe/ZnxCd1−xS/ZnS and CdSe/CdS/ZnS, respectively (**Figure 2**). These QRs are efficient, stable, and possess narrowband emission. **Figure 2** shows the scanning transmission electron microscopy (STEM) energy-dispersive X-ray spectroscopy (EDX) mapping for intermediate green-emitting CdSe/ZnxCd1−xS QRs and the same after covering with ZnS shell (CdSe/ZnxCd1−xS/ZnS) as well as for red-emitting QRs of configuration CdSe/CdS/ZnS. The QR dimensions are measured as 18 × 4 nm and 30 × 6 nm for green and red-emitting QRs, respectively. For green CdSe/ZnxCd1−xS QRs, Zn, S, Cd atoms are distributed throughout the rods confirming the gradient material composition. The CdSe seeds, on the other hand, can be confirmed by the Se atom signal that is located only in the inner part of the QRs (see **Figure 2a**). For core–shell–shell CdSe/CdS/ZnS red-emitting QRs, the Zn atoms are distributed throughout the thickness of the rods, whereas the outer shell of the QR consists of ZnS Only (see **Figure 2f–i**).

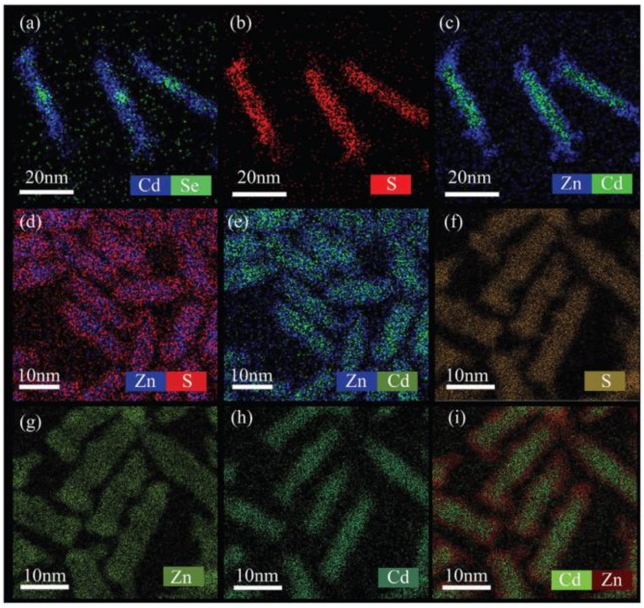

Figure 2 a–i) STEM image of red CdSe/CdS/ZnS QRs (a–c), green gradient alloyed CdSe/ZnxCd1−x S QRs (d,e), CdSe/ZnxCd1−xS/ZnS (f–i) elemental maps based on EDX scans for Zn, Cd, Se, and S.

The spectrum of the fabricated QRWLED consists of three emission band peaks at 450, 527, and 624 nm (see **Figure 3d**). The CIE color coordinate of the QRWLED with CCT ≈6500 K represents a good white balance. In LED arrays for the LCD backlight unit, the measured cladding temperature goes up to 85 °C to provide 300 nits of brightness for the LCD panel. Finally, we successfully demonstrate the 4.3 in. color enhanced display prototype by replacing the traditional phosphor-based LED LCD backlight with QR white LED (QRWLED) LCD backlight (see **Figure 3**). The measured brightness from the QRWLED LCD backlight is 6580 nits that reduces to 375 nits after the panel. The fabricated QR LCD shows pure white (**Figure 3a,b**) and saturated red and green color performance (**Figure 3c,d**). The color gamut of the display prototype equipped with a QRWLED backlight unit covers a wide color space of 118%NTSC and 90%BT2020 in CIE1931 color space, which is significantly larger than that of phosphor-based LED backlight LCDs (<75% NTSC).

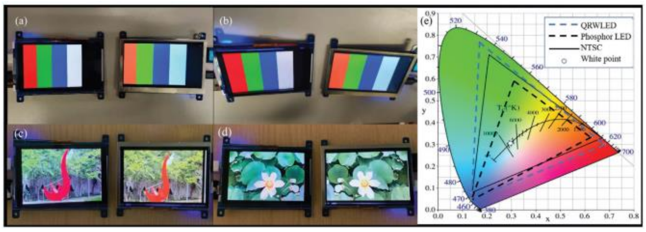

Figure 3. a) QRWLED backlight based 4.3 in. display prototype (left) and conventional display (right). b) Viewing angle dependence of display prototypes. c,d) Red and green display images. e) Color gamut between phosphor and QR-based display backlight.

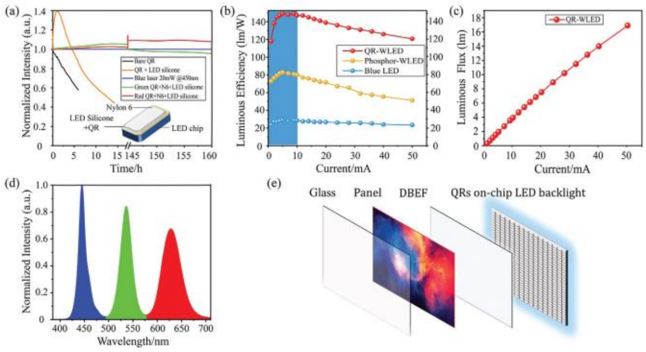

Figure 4. a) Comparison of photostability of bare QR, Nylon-6 encapsulated QR time-resolved photostability under blue laser excitation. b) Luminous efficiency of QRWLED, WLED based on phosphor and blue-chip. c) The luminous intensity versus current for white QRLEDs with blue LED source. d) Spectrum distribution of QRLED. e) Schematic of a QRs on-chip backlight with dual brightness enhancement film (DBEF) design for displays.

3. Conclusion

This study sets out to solve the PLQY quenching and stability issue of quantum rods in on-chip design. The introduction of outer gradient ZnxCd1−xS shell and ZnS shell for the core–shell dot in rod CdSe/ZnxCd1−xS/ZnS gradient alloyed quantum rods provides smoother confinement potential, reduces the nonradiative energy transfer, and leading to 81% solid-state PLQY. The proposed white quantum-rod LED chips provide luminous efficacy of 149 lm W−1 and color gamut of 118% NTSC and 90% BT2020 with high thermal and optical stability, which is highly suitable for LCD backlighting applications. Furthermore, material consumption has been significantly reduced compared to the state-of-the-art LEDs. The efficacy of QRWLED drops to 120 lm W−1 at the higher current (50 mA), but it is still substantially higher than the phosphor-based LEDs (≈50 lm W−1),

References

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