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Quantum dots: a new era for liquid crystal display backlight

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Size quantization effects bring a wide color gamut, enhanced light efficiency, and a tunable emission wavelength to quantum dot backlighting for liquid crystal displays.

Liquid crystal displays (LCDs) have become both ubiquitous and indispensable in our daily lives. They have, however, begun to face strong competition from organic LEDs (OLEDs). Both of these technologies present advantages and disadvantages. LCDs are low cost, feature low power consumption, and have a high resolution density. On the other hand, OLEDs achieve superior response times, vivid colors, flexibility, a high contrast ratio (in dark ambient), and allow a thinner profile. Blue phase LCD is currently being developed with the aim of reducing response times,[1] but color saturation must also be improved while maintaining high optical efficiency.

Great effort has been made toward improving LCD color performance. Presently, the majority of LCDs use single-chip white LED as backlight, comprising a blue LED with yellow phosphor. Due to the broad emission band of yellow phosphor, its color gamut is ∼75% of the AdobeRGB (red, green, blue) standard. Narrow-band green/red phosphor materials are under development, but their optical efficiency remains relatively low. Although discrete RGB LEDs can significantly extend the color gamut, they require complicated driving circuits.[2]

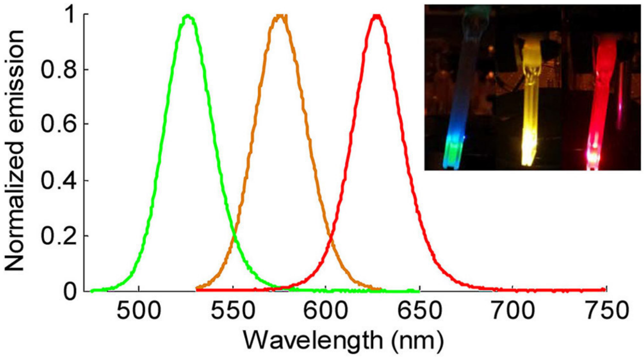

Figure 1. Emission spectrum of a quantum dot (QD) with a cadmium sulfide/selenide core and a zinc sulfide shell (CdS_xSe_{1-x}/ZnS: the ratio of CdS is x, while the ratio of CdSe is 1–x). Varying the composition or particle size alters the bandgap of the core, enabling a tunable emission wavelength. Inset shows the emission color when QDs are excited by a 459nm blue LED.

Quantum dot (QD) technology is emerging as a novel backlight source that could help to increase the color performance of LCDs. QDs are composed of nanoparticles with diameters of ∼5–20nm. When charge carriers (electrons and holes) are confined to such small particles, the larger bandgap of the surrounding material creates a barrier. The discrete energy levels that arise as a result of this barrier consequently dictate the material properties. This effect (size quantization) gives QDs several attractive features, including high quantum efficiency, a broad absorption band, narrow emission linewidth, and a controllable emission peak.[3] Figure 1 shows the emission properties of the QD samples that we used, which have a cadmium sulfide/selenide core and a zinc sulfide shell (CdS_xSe_{1-x}/ZnS: the ratio of CdS is a variable, x, while the ratio of CdSe is 1–x). Their luminescence is quite narrow (full width at half-maximum is ∼30nm), which yields highly saturated color emissions. In addition to this, the emission wavelength can be tuned by varying both the size and composition of the QD during material synthesis. Cadmium selenide QDs of different sizes, for example, can emit light from blue (450nm) through to red (700nm) wavelengths.

In our work, we used a blue LED to excite the green/red QD mixture, obtaining a white light with three distinguishable emission bands: see Figure 2(a). Conventional phosphor white LED has low spectral weights in the green and red regions, and color filters play a key role in differentiating between them. QD backlight, however, presents excellent color purity, which decreases the dependence of overall color performance on color filters. Moreover, it provides ‘smart’ backlighting. Depending on the display system requirements, the size and/or composition of the QD particle can be engineered to tune the emission wavelength, which can be made to match the transmission spectra of color

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filters to enhance light efficiency. Additionally, their central wavelengths can be optimized to encircle a larger color gamut area in the color space defined by the Commission Internationale de l'Eclairage (CIE). This unique feature leads to vivid color performance and increased energy efficiency.

To take advantage of the smart backlighting features enabled by the medium, we performed systematic modeling of LCD backlight. Using this information, we were able to optimize the QD spectrum for a wide color gamut and high light efficiency:[4] see Figure 2(b). Figure 3 depicts the performance of QD backlight in terms of these two objectives. Instead of obtaining one QD spectrum that simultaneously satisfies both objectives, we found a series of solutions with tradeoffs between light efficiency and color gamut. Due to the intrinsic exclusivity of the two objectives, it is not possible to preclude these tradeoffs. To enhance light efficiency, the three emission peaks must lie close to 550nm, where the human eye is most sensitive. On the other hand, color crosstalk must be reduced by separating these emission peaks to extend the color gamut. Given the series of solutions for different application and display requirements, we are able to select the most suitable solution according to the requirements.

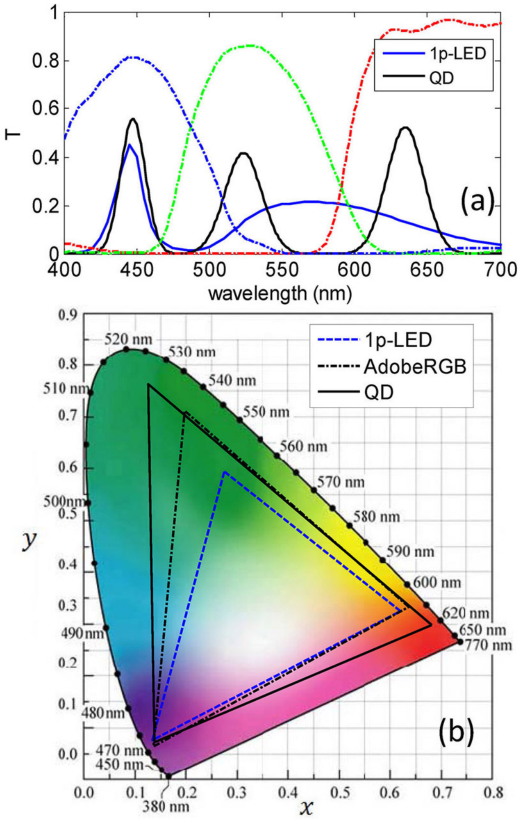

Figure 2. *(a) Transmission spectra of color filters, and emission spectra of QD backlight (CdS_xSe_{1-x}/ZnS) and single-chip white LED with yellow phosphor (1p-LED). (b) Color gamut in CIE 1931 (three spectral response curves standardized by the Commission Internationale de l'Eclairage) achieved by 1p-LED and QD. AdobeRGB (red, green, blue): An Adobe color space standard.*

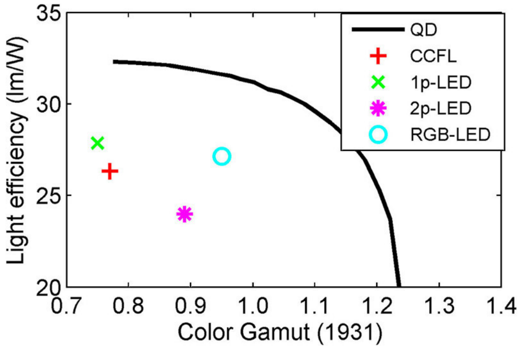

Figure 3. *Performance of QD backlight (CdS_xSe_{1-x}/ZnS) and various conventional backlights: cold-cathode fluorescent lamps (CCFL); 1p-LED; single-chip white LED with green and yellow phosphor (2p-LED); multi-chip RGB LEDs (RGB-LED).*[4]

The QD backlight has performance superior to conventional backlights: see Figure 3. The light efficiency of the QD backlight is $\sim$13% higher than that of RGB LEDs for the same color gamut. Moreover, if the light efficiency remains the same as that of RGB LEDs, the QD backlight is capable of achieving a color gamut of 118% AdobeRGB, a value much wider than that found in commercial OLED TVs ($\sim$100% AdobeRGB). In addition to these advantages, implementation of QD technology is cost-effective, reliable, and process-ready. On the material level, QDs can now be synthesized in large volumes at affordable cost ($5/milligram) with over 90% quantum efficiency and a $>50,000$-hour lifetime.[4] On the display system level, QDs can be dispersed in polymers and packaged in various forms for integration into commonly employed backlights.[5] The main technical challenge that remains is the development of nontoxic QD material that meets government legislation.[6]

In summary, color is a crucial differentiator between LCDs and OLEDs. QD backlighting could improve LCD performance in terms of color gamut and light efficiency, making them more competitive for use in future display technology. QD phosphor is also attractive for general LED-based lighting applications due to its high efficacy and superior color rendering. The main objective for QD research and development is to overcome the technical barriers preventing this novel technology from

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commercialization. With this aim in mind, we are currently developing a novel QD device with controllable emission direction and light polarization for use in LCD backlighting.

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