Colloidal Nanocrystal-Based Light-Emitting Diodes Fabricated on Plastic – Towards Flexible Quantum Dot Optoelectronics

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Abstract
We report the first demonstration of mechanically flexible quantum dot light-emitting-diodes (QD-LEDs) of all three RGB primary colors. The efficiencies of the flexible devices are high, suggesting the intrinsic flexibility of the QD-based optoelectronic devices.

Introduction

Recent advances in the synthetic techniques for growing high-quality colloidal quantum dots (QDs) of semiconductor compounds, such as (Zn,Cd)(S,Se) and (In,Ga)(As,P), have given rise to a new family of solution-processable inorganic chromophores featuring size-tunable color, narrow emission bandwidth, high photoluminescence (PL) efficiency, unmatched photochemical stability, and structural robustness. These superior properties render them promising building blocks for the next-generation thin-film optoelectronics, which has spurred the widespread interests of developing QD-based light emitting-diodes,[i,ii,iii,iv,v,vi,vii,viii,ix] hybrid photovoltaics,[x,xi] nanoscale lasers,[xii,xiii] etc.[xiv] Nonetheless, almost all of the QD devices investigated to date have been fabricated over rigid substrates such as glasses and semiconductor wafers, posing limitations to the manufacturing cost, flexibility, surface area, and portability in many potential QD applications.

In this work, QD-LEDs have been designed and fabricated over indium-tin-oxide (ITO)-coated poly(ethylene terephthalate) (PET) substrates, and they exhibited high brightness, saturated colors, and pronounced flexibility. The photographic images in Fig. 1(a) display the output of red, green and blue (RGB) QD-LEDs working in relaxed and bent states, respectively. The close-up view of the surface emission from the relaxed RGB LED pixels operated at a brightness of ~200 cd/cm^2 reveals the spectral and luminous uniformity across the device emissive regions. Devices in the bent samples were imaged at the maximum luminance (~7000 cd/m^2 for red, ~3300 cd/m^2 for red, ~1400 cd/m^2 for red) to highlight the bright emission from the flexible QD-LEDs. At high brightness, the LED images become whitish due to the saturation of the camera sensor pixels, while the periphery regions glow in the respective colors as a result of the back scattering. The narrow-band electroluminescence emission of RGB QDs, recorded at the maximum LED brightness, is centered at 624nm, 535nm, and 462nm, respectively, with the corresponding FWHM bandwidths as 28nm, 30nm and 22nm, respectively. There is no noticeable difference between the output spectra for relaxed and bent QD-LEDs. The organic emission in the QD-LED output has been minimized via controlling the HTL and ETL layer thicknesses in the device configuration design. Figure 1b shows the Commission Internationale de l'Eclairage (CIE) chromaticity coordinates for the red (0.62, 0.32), green (0.21, 0.75) and blue (0.16, 0.06) colors of the RGB flexible QD-LEDs with respect to the National Television System Committee (NTSC) color triangle. It is evident from the CIE plot that the triangle formed by connecting the color coordinates of the QD-LEDs largely encloses the NTSC color triangle, suggesting the superior colormetric properties of the flexible QD-LEDs towards their potential applications in full-color and high-definition flexible displays.

The 'flexibility' of the PET-based QD-LEDs was examined by investigating the performance of the device in the bent state under mechanical stress at different bending radii. The I-V and L-V characterization of the device bent into different states of curvature suggest that the observed declination of QD-LED brightness with the bending radius can be correlated to the reduced current density of the device under the same voltage bias condition. The luminous efficiency remains largely the same at any bending radii larger than ~5mm, suggesting that the EL performance of the QD layer in the LED active region was not subject to any degradation under mechanical stress. It is worth mentioning that the critical bending radius of our flexible QD-LEDs is below the bending limit of many possible applications, for instance, for smart cards, and further sufficient for large, roll-up, or conformable flat panel displays.[xv].

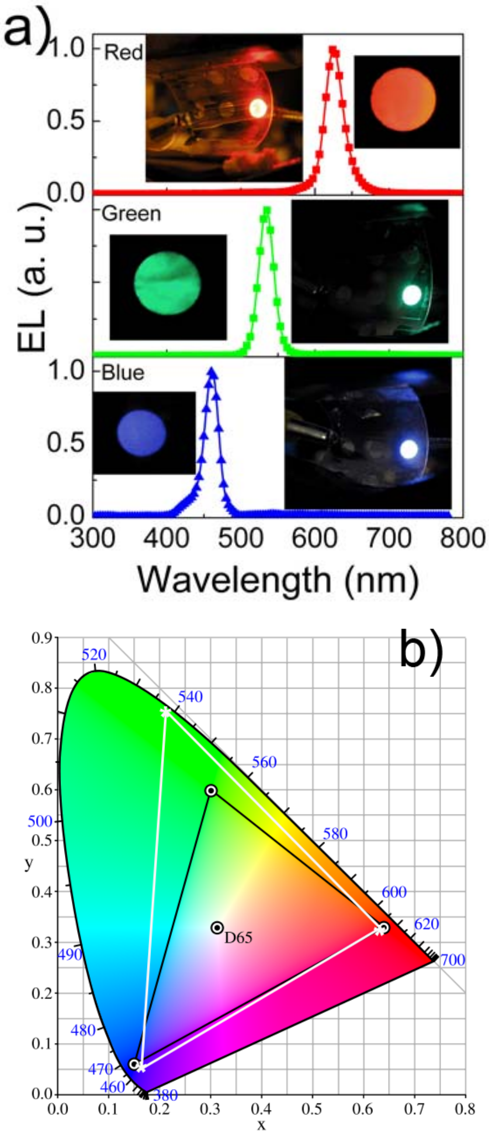

Figure 1 a) EL spectra of red, green and blue-emitting QD-LEDs operated at the maximum brightness. The insets show the images of relaxed RGB devices operated at low brightness and the bent RGB devices operated at the maximum brightness, respectively; b) CIE coordinates of the RGB QD-LED colors with respect to the NTSC color triangle.

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