High-density two-color micro-LED array based on brushing-assisted micropatterning of quantum dots

Dacheng Mao[1], Zheshun Xiong[1], Matthew Donnelly[1], and Guangyu Xu[1,*]
[1]Department of Electrical and Computer Engineering, University of Massachusetts, Amherst, Massachusetts 01003, USA
**Email: guangyux@umass.edu*

Abstract: We report a 17 μm-pitched two-color micro-LED array based on brushing-assisted micro-patterning of quantum dots. Filtered by an integrated distributed Bragg reflector layer, our array features bright, localized, and fast light output near 462 nm and 623 nm with low spectral and spatial crosstalk. © 2021 The Author(s)

OCIS codes: (230.3670) Light-emitting diodes; (220.4000) Microstructure fabrication.

Micron-size light emitting diodes (i.e. micro-LED) have emerged as essential integrated light sources with balanced brightness, power consumption, and lifetime [1]. Micro-LEDs with different colors, if placed in a high-density array form, will advance a variety of display and biomedical applications, thereby drawing much attention in recent years. To date, multi-colored micro-LED arrays are often built with complex fabrication processes, such as substrate transfer, nanocolumn engineering, and aerosol/ink jet printing of quantum dots (QDs) [2-6]. Among them, QD-based micro-LED arrays hold promise for high brightness, small pitch, and CMOS compatibility [4-6]; these arrays are, however, made by a delicate nozzle system that precisely sprays QDs onto the targeted LED pixels. To this end, here we present a 17 μm pitched two-color micro-LED array based on brushing-assisted micropatterning of InP/ZnS QDs (Fig. 1), aiming to develop a simple alternative method to achieve high-density multi-colored micro-LED arrays.

We first fabricated a cross-bar structured, GaN-based micro-LED array that can output 462/19 nm light using standard lithography and dry etching steps [7]. The 4-by-4 pixels were patterned in 7.8 μm-by-7.8 μm sizes and placed in a 17-μm pitch. To prepare the device for QD patterning steps, we next passivated the array with a 30 nm-thick Al_2O_3 layer, and coated a 7 μm-thick SU8 layer on top with 13 μm sized openings on select LED pixels to define the QD regions. Afterwards, we applied one drop of QD solution (25 mg/mL in toluene, emission at 623/45 nm) on the SU8-patterned array, where most of the solvent was evaporated in *ca.*1 min. We then placed the array in a glassware and immersed it in acetone. We observed that QDs can be partially resuspended in acetone and effectively brushed into the SU8 openings by a polydimethylsiloxane (PDMS) piece, likely due to the gravity of the QDs since their density is larger than acetone. To enhance the color conversion efficiency in QD-patterned LED pixels (i.e. red pixels), we chose to filter the array with an integrated distributed Bragg reflector (DBR) layer, which was achieved by evaporating 9 pairs of alternating SiO_2/TiO_2 (77 nm/48 nm) layers on top of a 48 nm thick TiO_2 layer. This thin-film based DBR layer served to reflect the 462/19 nm light leaked through the QD (from the LED pixel beneath), thereby improving the color purity and brightness at 623/45 nm. We finally applied dry etching steps to open the DBR layer on LED pixels with no QDs patterned on top (i.e. blue pixels), enabling their 462/19 nm light output.

We next examined the spectral and spatial crosstalk of our two-color LED array. In the former, we checked if DBR-filtered red LED pixels can effectively convert the LED illumination at 462/19 nm to the QD emission at 623/45 nm. Specifically, we used an inverted fluorescence microscope (Leica) to measure the light intensity of red pixels at 460/50 nm and 605/70 nm windows using blue and red fluorescence protein cubes, respectively (i.e. BFP and RFP intensities). Since our DBR layer was designed to effectively block 462/19 nm light with less than 1 % transmittance (Fig. 2a, measured with the DBR layer evaporated on a dummy glass slide), the ratio of RFP and BFP intensities increased from 0.24 to 3.7 after evaporating the DBR layer on the LED array (Fig. 2b), suggesting that our red pixels can output a significant amount of 623/45 nm light compared to the 462/19 nm light leakage. In the latter, we checked if the light output of individual LED pixels (blue pixel #1 and red pixel #4 in Fig. 1b) would leak to neighboring QD regions on red pixels (Fig. 2c), which would lead to spatial crosstalk of the RFP intensities. Our data show that: 1) when a single red pixel illuminates, its RFP intensity is 14.97 times brighter than those in the QD regions of other 7 non-illuminating red pixels; 2) when a single blue pixel illuminates, the resultant RFP intensities in the QD regions of all 8 red pixels are 7.81 times weaker than the RFP intensity of a single illuminating red pixel (i.e. QD region #2 in Fig. 2c). These results suggest low spatial crosstalk in our QD-patterned two-color LED array .

We further characterized the optoelectronic performance of the array by measuring the brightness, spot size, and response time of individual pixels (Fig. 3). Specifically, our data show that when the biasing current of the LEDs (I_{LED}) increased up to 4 μA, blue pixels can output 1 mW/mm^2 optical power density (P_{light}) with its full-width at half maximum (FWHM) being *ca.* 10 μm, whereas red pixels can output 0.07 mW/mm^2 P_{light} with their FWHM being *ca.* 15 μm. We also found that the QD-patterned red pixel can reliably be switched at 40 Hz with *ca.* 2 ms rising/falling times. These figures of merit are on par with the prior multi-colored micro-LED arrays based on an aerosol/ink jet printing process [5].

In sum, we developed a DBR-filtered two-color micro-LED array based on brushing-assisted micro-patterning of QDs on top of blue LED pixels. Our array featured bright, localized, and fast light output near 462 nm and 623 nm with low spectral and spatial crosstalk, suggesting the promise of our brushing-assisted fabrication method in achieving high-density multi-colored micro-LED arrays.

Acknowledgement: This work was in part supported by NSF under grant ECCS-1835268. The authors thank Amir Arbabi and Yubing Sun for technical assistance.

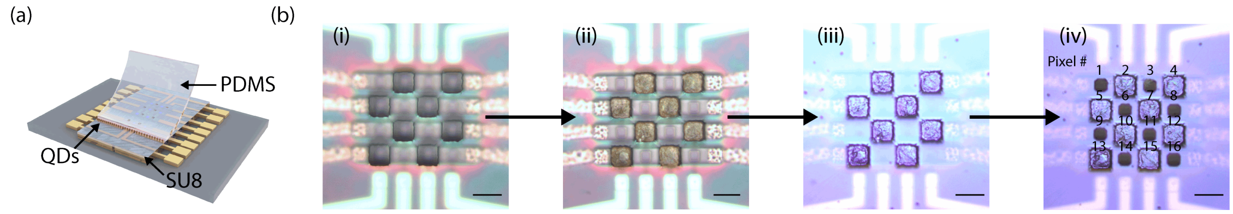

Figure 1. **Array fabrication.** (a) Illustration of brushing-assisted micropatterning of QDs via a PDMS piece. (b) Device images at each fabrication step, including (i) SU8 openings on the micro-LED array; (ii) QDs brushed into SU8 openings; (iii) QD-patterned array covered by a DBR layer; and (vi) DBR openings on LED pixels without QDs. Scale bar, 20 µm.

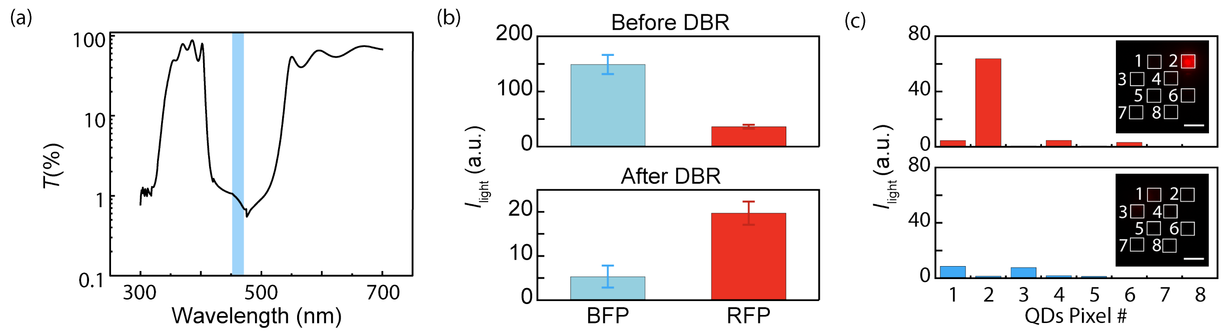

Figure 2. Spectral and spatial crosstalk of the two-color LED array. (a) Transmittance spectrum of the DBR layer. Blue shaded area represents the emission bandwidth of the blue LED. (b) Averaged BFP and RFP intensities (I_{light}) from 8 red pixels before and after evaporating the DBR layer on top of the array. All pixels were biased at $I_{\mathrm{LED}} = 1$ µA. Error bars represent ±1 s.d. (c) RFP intensities (I_{light}) from the QD regions of 8 red pixels (labeled as 1-8) when one single red pixel (pixel #4 in Fig. 1b) or one single blue pixel (pixel #1 in Fig. 1b) was illuminated, respectively. Both pixels were biased at $I_{\mathrm{LED}} = 4$ µA.

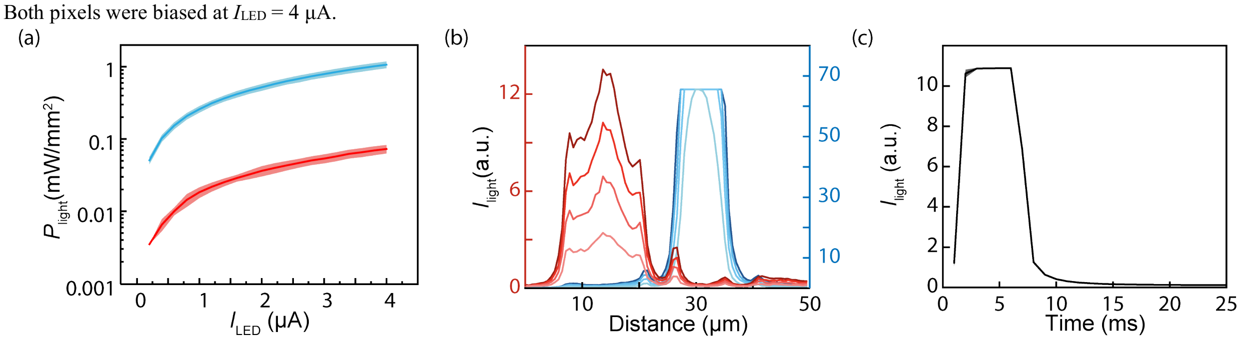

Figure 3. Array characterization. (a) P_{light} vs I_{LED} in both blue and red pixels. (b) Spatial profile of the pixel output (red pixel #5 and blue pixel #6 in Fig. 1b) at the array surface with I_{LED} ranging from 1 to 4 µA. (c) Pixel output (red pixel #2 in Fig. 1b) pulsed with a 10 ms pulse duration at 40 Hz pulsing frequencies. The pixel was biased at $I_{\mathrm{LED}} = 4$ µA. In (a) (c), shaded areas represent ±1 s.d.

[1] Lin, J. Y. *et al*. Development of microLED. *Appl. Phys. Lett.*116.10: 100502 (2020).
[2] Li, Yang. *et al*. 48× 48 pixelated addressable full-color micro display based on flip-chip micro LEDs. *Appl. Opt.* 58.31: 8383-8389. (2019)
[3] Kishino, Katsumi. *et al*. Two-dimensional multicolor (RGBY) integrated nanocolumn micro-LEDs as a fundamental technology of micro-LED display. *Appl. Phys. Express* 13.1: 014003. (2019)
[4] Chen, Guan-Syun. *et al*. Monolithic red/green/blue micro-LEDs with HBR and DBR structures. *IEEE Photon. Technol. Lett* 30.3: 262-265. (2017)
[5] Lin, Huang-Yu. *et al.* Optical cross-talk reduction in a quantum-dot-based full-color micro-light-emitting-diode display by a lithographic-fabricated photoresist mold. *Photonics Res*.5.5:411-416 (2017).
[6] Chen, Sung-Wen. *et al.* , Full-color monolithic hybrid quantum dot nanoring micro light-emitting diodes with improved efficiency using atomic layer deposition and nonradiative resonant energy transfer," *Photon. Res.* 7, 416-422 (2019)
[7] Mao, D. et al. Single-cell optogenetic control of calcium signaling with a high-density micro-LED array. *iScience*, 21, 402-413 (2019).