Active Matrix Monolithic Full-Color LED Micro-display

Longheng Qi[1], Xu Zhang[1], Wing Cheung Chong[1], Peian Li[1], Chak Wah Tang[1], and Kei May Lau[1]

[1]Department of Electronic and Computer Engineering, HKUST, Clear Water Bay, Kowloon, Hong Kong SAR
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ABSTRACT

An active matrix monolithic full-color LED micro-display is demonstrated, combining monolithic blue GaN-on-Si LED array and quantum dots down conversion technology. This full-color scheme shows feasible manufacturability and visual quality, paving a new pathway toward volume production of full-color LED micro-display in the near future.

1 INTRODUCTION

Micro-display is currently undergoing a period of rapid development with high demand driven by various applications such as augmented reality (AR), virtual reality (VR), and wearable devices. Micron-sized GaN light-emitting diode (µLED) is one of the most promising candidates for micro-display due to its superior properties including high brightness, long lifespan and low power consumption. However, the practical application of GaN µLED has been seriously hindered by the challenges in realizing full-color schemes. The mainstream to develop full-color LED micro-display is the transfer-printing technology [1] in which red, green and blue LED chips are selected from separate wafers then assembled on the same display panel. Nevertheless, the equipment cost and transfer yield become issues as the pixel size scales down. We, and other researchers have developed another approach based on down conversion technology by jet printing red, green and blue QDs on a monolithically-fabricated UV LEDs array [2], but the jet printing process efficiency will limit the feasibility of volume production especially for high-resolution micro-displays. Instead of jet printing, QDs pristine solution can be mixed with photoresist (QDs-PR) and then patterned using a lithography-based method [3], bringing efficient and large-scale manufacturability. Furthermore, monolithic blue LEDs array was adopted, leading to a simplified process owing to that only green and red QDs conversion layers need to be patterned.

This paper is organized as follows: Section 2 describes the detailed fabrication procedures of full-color LED micro-display. Section 3 presents the conversion properties of QDs-PR and the display performance of this full-color micro-display, respectively. Finally, a brief conclusion is drawn in section 4.

2 EXPERIMENT

This section illustrates the details about the design and fabrication of our full-color active matrix LED micro-display. The key parts including µLED array, CMOS backplane, pixel driver design and QDs-PR patterning are discussed.

2.1 µLED Array and CMOS Backplane

The µLED array was fabricated using InGaN/GaN epilayers grown on Si substrate by Metal Organic Chemical Vapor Deposition (MOCVD). The fabrication procedures of this µLED array proceeds as follows: first, a layer of 115nm-thick indium tin oxide (ITO) was deposited on the p-GaN layer by e-beam evaporation and patterned by wet etching in 1:100 diluted aqua regia for 2mins. Then individual µLEDs were defined by dry etching the GaN down to the n-GaN layer using the patterned ITO as a self-aligned mask. After annealing in O_2 and N_2 atmospheres respectively, the ITO layer formed an ohmic contact to the p-GaN. Cr/Al based metal stack was then deposited on top of the ITO and n-GaN layer as p- and n-electrodes, respectively. The common n electrode was designed as a grid structure, thus reducing the number of bonding pads and also providing uniform current flow in each subpixel for uniform light output power. Next, the wafer was passivated by spin coating of a 1um-thick overcoat photoresist, followed by opening holes on top for both p- and n-electrodes. A single layer of indium was then deposited and reflowed as the bonding bumps to flip-chip bond the µLED array and CMOS backplane. Fig. 1 (a)-(c) demonstrate the process flow of a monochromatic active matrix LED micro-display.

After flip-chip bonding, the Si growth substrate was removed by a SF_6-based reactive ion etching (RIE) process to expose the smooth and crack-free GaN layers in display regions [4], which consists of 64 × 36 subpixels in size of 40 µm × 40 µm. The size of this integrated chip after flip-chip bonding was 4.5mm in length and 2.8mm in width as shown in Fig. 2.

2.2 Pixel Driver Design

The CMOS backplane was fabricated using a 0.18 µm bulk CMOS process, consisting of a pixel driver, a scan driver, a data driver and a hybrid voltage regulator. The voltage regulator is designed for the step-up and step-down voltage conversion to overcome the voltage

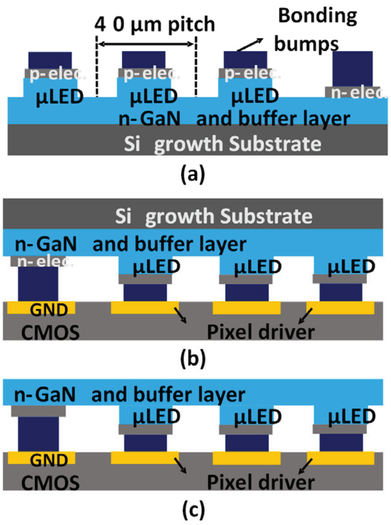

Fig. 1 Process flow of active matrix monolithic micro-display

(a) Fabrication of blue µLED array. (b) Flip-chip bonding of µLED array and active matrix CMOS backplane. (c) Si growth substrate removal.

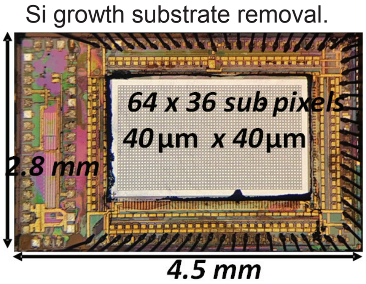

Fig. 2 Integrated chip

Microscope image of Integrated chip after flip-chip bonding and Si growth substrate removal.

fluctuation of the battery. A pixel driver shown in Fig. 3 consists of three transistors *M1*, *M2*, *M3* and one capacitor C_S, where *M1* is a row scanning switch transistor, *M2* functions as a current source, *M3* is the row global enable switch transistor, C_s behaves as a data storage. The row scanning procedure starts when row scanning signal R_s becomes 0 and row global enabling signal R_{en} becomes 1, transistor *M1* turns on and column data C_{data} is written into the storage capacitor C_s. Then the voltage across C_s is applied to *M2* as the gate-source voltage, thus controlling the current flow of µLED. After all the columns data have been stored in C_s of this row sequentially, R_s becomes as 1 and the row scanning procedure moves to next row. When all subpixels are loaded with the display data, R_{en} is enabled to activate the display.

2.3 QDs-PR Patterned Array

Red and green light emitting CdSe/ZnS QDs dispersed in toluene were mixed with a commercial photoresist with a proper ratio to get a QDs-photoresist (QDs-PR) that can be patterned using photolithography process. For green QDs, fine patterns can be well

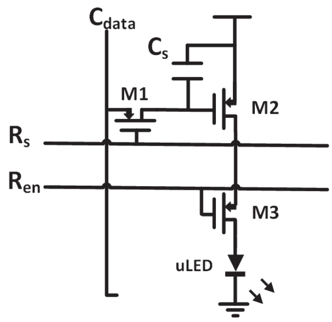

Fig. 3 Schematic of subpixel driver circuit

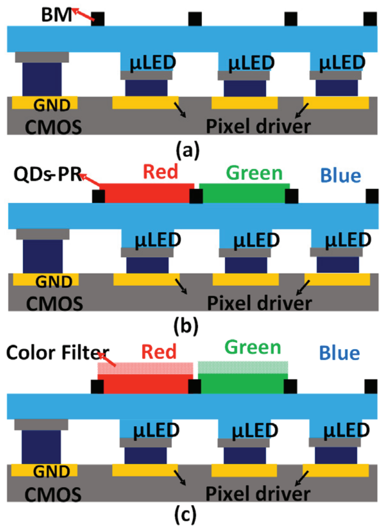

Fig. 4 Process flow of QDs-PR patterning

(a) Black matrix layer patterning. (b) QDs-PR patterning. (c) Color filter patterning.

defined by tuning the mixing proportion of QDs pristine solution to PR as 2:1 while the mixing ratio of red QDs-PR was modified to 3:2. The above active matrix blue LED micro-display can be extended to full-color by applying the QDs-PR patterning process directly on the chip. The simplified process flow is depicted in Fig. 4.

A layer of black matrix (BM) was first patterned to suppress the light crosstalk between subpixels (Fig. 4(a)). Then 3-µm-thick red and green QDs-PR layers were patterned on red and green subpixels, respectively (Fig. 4(b)). 1.5-µm-thick color filter was adopted to block the unabsorbed blue light for red and green subpixels (Fig. 4(c)).

Fig. 5 (a)-(c) present well-defined patterns of QDs-PR and color filter (CF) on fully exposed GaN layer, respectively. Bayer matrix was adopted to configure four subpixels (RGGB) as one full-color pixel, as depicted in Fig. 5(d). The blue subpixels, with the strongest emission, were exposed without QDs-PR and CF patterning.

3 RESULTS

Separate experiments were performed to estimate the conversion properties of the QDs-PR. The QDs-PR was spin coated on thin glass (~150-µm-thick) with

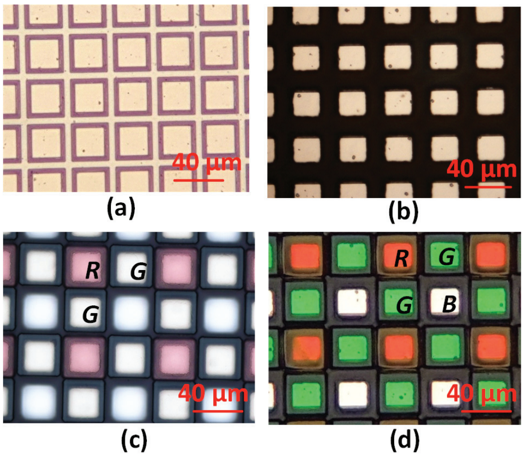

Fig. 5 QDs-PR and CF patterned array
(a) microscope image of exposed display region. After (b) black matrix, (c) QDs-PR, and (d) color filter patterning.

different thickness. A blue LED with peak emission wavelength of 440 nm, fabricated using the same epiwafer, was packaged as the light source to excite the QDs-PR layer to emit red/green light. The conversion efficiency was estimated by calculating the ratio of the converted light output power to the blue light source power. As shown in Fig. 6, higher conversion efficiency was observed using thicker red QDs-PR. Around 10% efficiency was estimated for 10-μm-thick red QDs-PR. Table I summarizes the conversion efficiencies of red and green QDs-PR with different thicknesses. The conversion efficiencies were found to be low for thin QDs-PR especially for the green one.

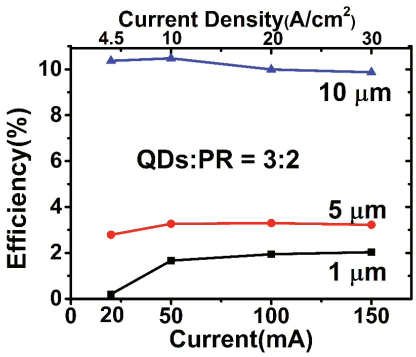

Fig. 6 Conversion efficiencies of red QDs-PR (3:2) of different thickness

Table I. Conversion Efficiencies of QDs-PR

QDs-PR Thickness	*1 μm*	*5 μm*	*10 μm*
Red QDs : PR	1.66%	3.27%	10.48%
Green QDs : PR	1.30%	2.58%	3.67%

Controlled by the Arduino DUE board, full-color images were rendered on the micro-display panel, as shown in Fig. 7. The electroluminescence spectra of red and green subpixels are weaker compared to that of

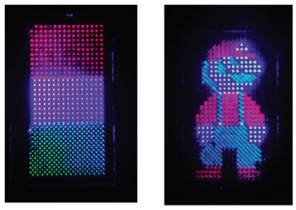

Fig. 7 Full-color images rendered on the micro-display

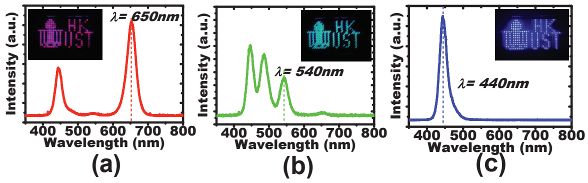

Fig. 8 Electroluminescence spectra
(a) red and (b) green and (c) blue. The insets are the corresponding displayed images.

blue ones, as shown in Fig. 8 (a)-(c). The dominant wavelength of red, green and blue are 650nm, 540nm and 440nm, respectively. The green dominant peak was weaker than that of the unabsorbed blue light even after the light filtering of green color filter. Both of the red and green light conversion can be further improved with better and thicker QDs-PR layer.

4 CONCLUSIONS

To conclude, a full-color LED micro-display was demonstrated, combining blue μLEDs using GaN-on-Si epilayers and lithography-based QDs patterning method. The color purity can be further improved through process engineering. This methodology exhibits feasible manufacturability of GaN-on-Si LED micro-display and paves a new pathway toward volume production of full-color LED micro-display in the near future.

REFERENCES

[1] Meitl, M.A., Radauscher, E., Rotzoll, R., Raymond, B., Bonafede, S., Gomez, D., Moore, T., Prevatte, C., Fecioru, A.I.M., Trindade, A.J. and Bower, C.A., "19 - 4: Invited Paper: Emissive Displays with Transfer - Printed Microscale Inorganic LEDs," SID Symposium Digest, Vol. 48, No. 1, pp. 257-263 (2017).
[2] Han, H.V., Lin, H.Y., Lin, C.C., Chong, W.C., Li, J.R., Chen, K.J., Yu, P., Chen, T.M., Chen, H.M., Lau, K.M. and Kuo, H.C., "Resonant-enhanced full-color emission of quantum-dot-based micro LED display technology," Optics Express 23, No.25, pp. 32504-32515 (2015).
[3] Lin, H.Y., Sher, C.W., Hsieh, D.H., Chen, X.Y., Chen, H.M.P., Chen, T.M., Lau, K.M., Chen, C.H., Lin, C.C. and Kuo, H.C., "Optical cross-talk reduction in a quantum-dot-based full-color micro-light-emitting-diode display by a lithographic-fabricated photoresist mold," Photonics Research 5, No. 5, pp. 411-416 (2017).
[4] Zhang, X., Li, P., Zou, X., Jiang, J., Yuen, S.H., Tang, C.W. and Lau, K.M, "Active Matrix Monolithic LED Micro-Display Using GaN-on-Si Epilayers," IEEE Photonics Technology Letters 31, No. 11, pp. 865-868 (2019).