Monolithic Micro-LED Full-Color Micro-Displays

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ABSTRACT

Monolithic LED arrays with color conversion schemes for full-color displays will be reported. Two micro-LED arrays fabricated using blue and dual wavelength LED epilayers are extended to full-color by quantum-dot down conversion technology. Both approaches exhibit feasible manufacturability and decent visual quality, showing promise toward volume production of full-color micro-displays.

1 INTRODUCTION

Micron-sized GaN LED has emerged as one of the most promising candidates for the next generation micro-display because of its superior properties including high brightness, long lifespan, operating temperature range and low power consumption, compared with other existing micro-display technologies.

Considering the emission of GaN-based LED is largely monochrome, typically in blue, violet, or green, fabrication of a monochromatic LED micro-display can be realized using conventional LED epilayers and precise process control. We have reported high-resolution monolithic micro-displays since several years ago, including a world-first 1700 pixels per inch (PPI) passive-matrix (PM) blue micro-display in 2014 [1] and a 400 × 240 active-matrix (AM) blue micro-display in 2016 [2]. Nevertheless, full-color schemes have been severely hampered by the difficulties of including three types of quantum wells (QWs) in the same GaN epilayers to emit the three primary colors monolithically. Moreover, it is not practical to apply red GaN LEDs to a full-color micro-display due to their extremely underdeveloped efficiency compared with the blue and green. There have been considerable attempts to develop LED full-color micro-displays. However, it remains a tremendous challenge, yet to be adequately resolved.

The mainstream approach, namely mass-transfer technology [3], is pioneered by LuxVue (acquired by Apple in 2014), in which individual red, green and blue (RGB) micro-LED chips fabricated on separate epitaxial wafers are assembled on a full-color micro-display panel. The enormous challenge of this approach is ensuring 100% yield in placement of the subpixels. Moreover, this approach becomes more impractical with decreasing yield when subpixel sizes get smaller (<10 μm), seriously hindering its application in near-to-eye displays such like augmented reality (AR) and virtual reality (VR), which may ultimately require subpixels much smaller than 10 μm. Unlike the transfer technology, we combined 3 monolithic LED arrays using a trichroic prism to demonstrate a novel 3LED light engine that can project red, green and blue images synchronously to generate full-color ones on a screen [4].

The other option to realize LED full-color micro-displays, as pioneered by our group, is based on color down conversion technology [5]. Starting with an UV LED array, designed and fabricated monolithically, we used red, green and blue CdSe/ZnS quantum dots (QDs) dispersed in toluene and then jet-printed on RGB subpixels, independently. Compared with the mass-transfer technology, this scheme inherits the advantages of monolithic fabrication of a micro-LED array but still faces several bottlenecks especially on the jet-printing technology. The QDs printing process requires a precise and time-consuming operation of three kinds of QDs on three different subpixels, and as a result, the production efficiency of jet-printing will become issues with increasing resolution and pixel density of the micro-displays. Moreover, the thickness of QDs layer is formidable to accumulate due to the spreading effect of the low-viscosity organic solvent, leading to insufficient light conversion and unsatisfactory full-color display quality. Consequently, there is much room for improvement for this full-color scheme.

Instead of jet-printing, we found that a lithography-based patterning process to form a QDs color conversion layer on pixels is more suitable for full-color micro-display applications. In this process, the QDs can be dispersed in a photosensitive solution and then finely patterned in large/full area of the wafer by the standard and undemanding photolithography process. Thus, the production efficiency and practicality will be remarkably better compared to jet-printing. Based on this method, Sharp Corporation demonstrated a full-color micro-display using blue micro-LEDs grown on sapphire substrate [6]. The transparent sapphire substrate used for growth was removed by laser lift-off process (LLO).

In our work, we explore different approaches to demonstrate monolithic micro-LED full-color micro-displays. First, large-scale and low-cost GaN-on-Si blue LED epilayers are employed to fabricate the micro-LEDs array. After flip-chip bonded with an AM CMOS backplane, the Si growth substrate was removed using a simple and low-cost SF_6-based dry etching process. Then red and green CdSe/ZnS QDs dispersed in commercially available and highly transparent photoresist (QDs-PR) were patterned on the micro-LED array, respectively using the photolithography process. In the second approach, we investigated the possibility of using blue/green dual wavelength LED epilayers to achieve full-color display, by growing blue and green QWs sequentially in the same LED structure on sapphire substrates. A PM driven micro-LEDs array was monolithically fabricated with topside-emitting configuration. Then red QDs dispersed in photoresist was patterned on the red subpixels.

2 EXPERIMENT

The implementation of full-color micro-displays can be divided into two steps. First, a monolithic micro-LED array was fabricated using blue or dual wavelength LED epilayers. Secondly, the QDs-PR was prepared and patterned on the monolithic micro-LEDs array to realize full-color micro-displays.

Red and green light emitting CdSe/ZnS QDs dispersed in toluene were mixed with a commercial photoresist with a critical ratio to get a stable QDs-PR that can be patterned using photolithography process. For green QDs, fine patterns can be well defined by tuning the mixing proportion of QDs pristine solution to photoresist as 2:1 while the mixing ratio of red QDs-PR was modified to 3:2.

2.1 Blue LED and Red/Green Colors Conversion

The blue micro-LED array was fabricated using InGaN/GaN epilayers grown on Si substrate by MOCVD. The fabrication procedures of this micro-LED array has been reported in our previous publications [7]. After flip-chip bonding on a CMOS backplane, 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, which consists of 64 × 36 subpixels in size of 40 μm × 40 μm. QDs-PR can be patterned directly on the bonded chip. Another option is to pattern the QDs-PR on a piece of thin glass first and then flip-chip bonded on the integrated LED chip. The production yield of this option could be higher because the micro-LED fabrication and QDs-PR patterning process are independent. Fig. 1(a) shows the structure of the QDs-PR patterning process on a piece of thin glass, Black matrix (BM) followed by red and green color filter (CF) were defined in red and green subpixels. Multi-layers of QDs-PR were spin-coated on the wafer with a targeted thickness of 10 μm patterned following the Bayer matrix (RGGB) configuration. A second layer of BM further suppresses crosstalk and helps the flip-chip bonding of the thin glass with the LED chip (Fig. 1(b)). Fig. 2 (a)-(c) illustrate the electroluminescence spectra of red, green and blue subpixels, respectively. The dominant wavelengths of converted red (650 nm) and green (540 nm) light suggest effective color conversion and crosstalk suppression. Fig. 2 (d)-(e) show typical images rendered on the micro-display panel.

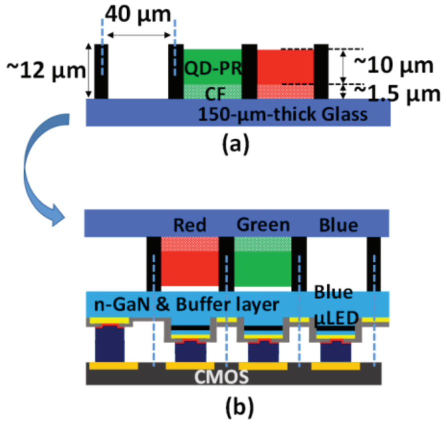

Fig. 1 Schematic of full-color micro-display using Blue micro-LEDs

(a) Structure of QDs-PR patterns on thin glass. (b) Schematic after the thin glass flip-chip bonded on the integrated LED chip.

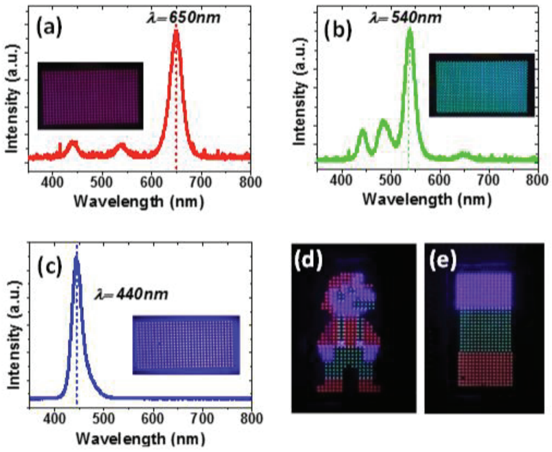

Fig. 2 Display results of the Full-color micro-display using blue micro-LED

Electroluminescence spectra of (a) red, (b) green, and (c) blue subpixels. The insets in (a)-(c) are the corresponding displayed images. (d)-(e) Full-color images displayed on this micro-display.

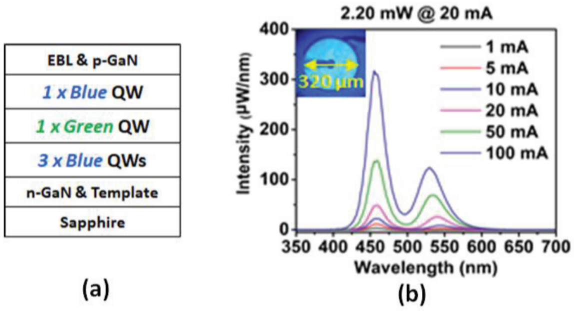

Fig. 3 Dual wavelength LED

(a) Simplified structure of dual wavelength LED. (b) Electroluminescence spectra of a conventional LED with a diameter of 320 μm.

2.2 Dual wavelength LED and Red Color Conversion

The dual wavelength LED epilayer was grown on a c-plane sapphire substrate in the same MOCVD system. The typical structure (yet to be optimized) is shown in Fig. 3, in which the QWs consists of one green quantum well (QW) sandwiched between one blue QW on top and three blue QWs underneath. The capping blue QW is applied to suppress the radiative recombination in the green QW thus to achieve a blue-dominant dual wavelength emitting property, which will facilitate pumping the red QDs light conversion. Fig. 3 (b) depicts the electroluminescence spectra of a conventional LED with a diameter of 320 μm. Blue-dominant emission with blue peak at 460 nm and a green peak at 530 nm are observed at different driving current densities.

The micro-LED array was monolithically fabricated with a PM driving scheme and a topside-emitting configuration. The display panel consisted of 40 × 40 pixels with 120 μm × 120 μm pitch. Each pixel included stripe arranged RGB subpixels that had pitch size of 40 μm × 120 μm. Red QDs-PR is patterned on red subpixels while the blue and green subpixels are planarized using overcoat photoresist (EOC). RGB CFs are capped on RGB subpixels independently to eliminate the undesired light components.

Fig. 4 (a) presents the electroluminescence spectra of the red, green, and blue subpixels. The peak wavelength of the RGB subpixels were 621 nm, 524 nm and 445 nm respectively. As shown in Fig. 5 (b), each die of the display including peripheral bonding pads was in size of 11 mm × 7.8 mm and the panel region was a 4.800 mm × 4.800 mm square. RGB bars with 8 different grayscale levels are displayed on this micro-display. A few dead lines were observed on the display panel, which can be eliminated by precise process control.

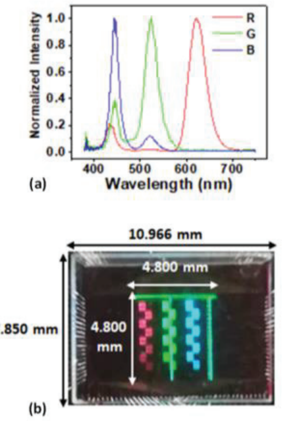

Fig. 4 Display results of the Full-color micro-display using dual wavelength micro-LED
(a) Electroluminescence spectra of red, green, and blue subpixels. (b) Full-color micro-display panel with image rendered.

3 CONCLUSIONS

Combining micro-LED and QDs conversion technologies, two monolithic full-color micro-displays were demonstrated using blue and dual wavelength LED epilayers, respectively. The blue LED epilayers were grown on Si substrate, benefiting from its low cost and large scale. The dual wavelength LED epilayers on sapphire substrate presented blue and green light emissions in single micro-LED, which would improve the display quality and simplify the QDs patterning process. The lithography-based QDs patterning process was employed to elevate the conversion properties and production efficiencies.

Feasible manufacturability and decent display quality have been demonstrated on both full-color micro-displays, indicating promising solutions for volume production of full-color micro-displays in the near future. It is strongly believed that both approaches will be able to be extended to high-resolution with improved color gamut and brightness by refinement of the process.

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