Monolithic Approaches to Implement Micro-LED Full-Color Micro-Displays towards Mass Production

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ABSTRACT

Starting from different LED epi-wafers, multiple monolithic approaches to implement micro-LED full-color micro-display are discussed in this paper. Feasible manufacturability and decent visual quality are demonstrated, showing enormous potential of micro-LED full-color micro-displays for augmented reality (AR) applications.

1 Introduction

Augmented reality (AR) technologies have witnessed unprecedented growth in the past several years, due to its widely accepted user experience in various applications, including healthcare, entertainment, navigation, and so on [1]. A multitude of commercial AR prototypes or products have been announced by market leaders such as Microsoft, Apple, and Google. Currently, most of the AR manufacturers set up the display module adopting existing technologies, Liquid Crystal on Si (LCoS) or organic light-emitting diode (OLED). However, LCoS provides limited contrast ratio, while a power-consuming backlit is typically required. Although OLED features self-emissive pixels, challenges like brightness, efficiency and lifetime are yet to be adequately addressed.

In contrast, inorganic LED technologies are capable to deliver much higher brightness together with long lifespan and device robustness, making it a promising and advantageous alternative for AR applications. To adopt the inorganic LED technologies, pixel transfer is the most straightforward means, in which red, green, and blue micro-LEDs are fabricated separately then picked and placed on the same display panel [2]. This approach has been successfully applied to fabricate mini-LED backlit, and large display panels. But it is not practical for micro-displays in AR applications which ultimately require subpixels smaller than 10 μm. Instead, monolithic fabrication approaches have proven more compact and efficient, as all the critical dimensions are defined by photolithography [3,4]. The primary challenge of monolithic approaches is the demonstration of full-color display based on the conventional monochromatic epilayers.

Our group have been focusing on monolithic micro-LED micro-display since mid-2000s. First, we developed monochromatic micro-displays with decent display quality and high resolution, including a world-first 1700 pixels per inch (>800 PPI) passive-matrix (PM) blue micro-display [5] and a 400 × 240 active-matrix (AM) blue micro-display [6,7]. Further, we explored multiple approaches to extend the monochromatic micro-displays to full-color ones. On the one hand, using the large-scale and low-cost GaN-on-Si blue LED epilayers, micro-LED arrays were monolithically fabricated [7,8]. With red and green CdSe/ZnS quantum dots photoresist (QDPR) patterned on top of micro-LEDs, full-color micro-displays were achieved [9,10]. Another approach is using dual wavelength LED structures to obtain blue and green light emissions on the same epi-wafer, which significantly simplified the full-color display realization as only red light emission had to be integrated with the monolithically-fabricated micro-LED array. In addition to red QDPR [11], another option is the hybridization of red AlGaInP micro-LEDs with dual wavelength micro-LED array via flip-chip bonding.

2 Experiment

2.1 Blue LED and Red/Green QDPR

As shown in Fig. 1(a), based on GaN-on-Si blue LED epilayers, the micro-LED array was firstly fabricated and integrated with the AM CMOS backplane. Then the Si growth substrate was removed by dry etching [8,9] or wet etching [7,10] to expose the display area. To follow up, the red and green QDPR were patterned on a transparent substrate to form a color conversion layer, following the Bayer matrix (RGGB) configuration. Then the color conversion layer was flip-chip bonded on the micro-LED array to realize a full-color micro-display (Fig. 1(b)).

To begin development of the color conversion technology, a 64 × 36 blue micro-LED array was fabricated, with a pixel pitch size of 40 μm and a density of 635 pixels per inch (ppi) [8]. Fig. 2 (a) presents the top-down view of the full-color micro-display chip after flip-chip bonding the color conversion layer on the blue micro-LED chip. The blue micro-display was easily transformed to a 32 × 18 full-color micro-display with a pitch size of 80 μm ×80 μm and a pixel density of 317 ppi. Fig. 2 (b) demonstrates two full-color images displayed on this micro-display.

Afterward, a high-resolution blue micro-LED array, consisting of 400 × 240 pixels with a pixel pitch size of

30 μm, was monolithically fabricated using 4-inch

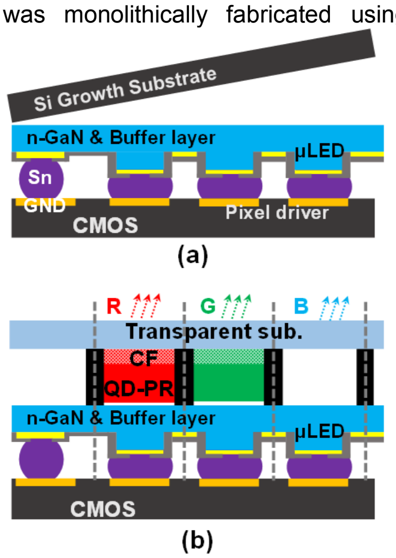

Fig. 1 (a) Structure of the integrated blue micro-LED chip. (b) Schematic of full-color micro-display using blue micro-LEDs and Red/Green QDPR.

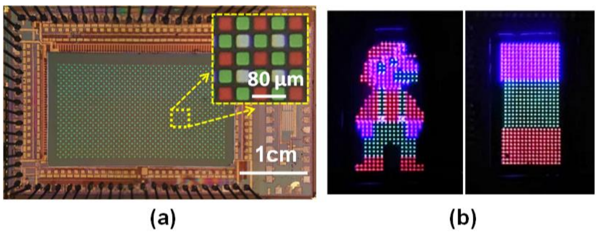

Fig. 2 (a) 32 × 18 full-color micro-display chip. Inset is a zoomed-in image of the color conversion layer. (b) Full-color images rendered on this full-color micro-display system.

commercial GaN-on-Si epi-wafers [7,10]. Fig. 3 (a) illustrates the 4-inch wafer after micro-LED fabrication, exhibiting the uniform and high-yield process. Fig. 3 (b) displays the blue micro-display chip when all the pixels are powered on with a total input current of 100 mA. The color conversion layer was also fabricated on a 4-inch transparent substrate (Fig. 3 (c)). Fig. 3 (d) shows one die of the color conversion layer after dicing. Electroluminescence (EL) spectra of red, green and blue subpixels were characterized as shown in Fig. 3 (e), respectively. The dominant wavelengths of converted red (640 nm) and green (530 nm) emission suggest satisfactory color conversion and suppression of crosstalk. Fig. 3 (f) show representative full-color images rendered on the micro-display panel.

2.2 Dual wavelength LED and its extension

The blue/green dual wavelength LED epilayers were grown on a 2-inch (0001) sapphire substrate by metal-organic chemical vapor deposition (MOCVD). Green and blue quantum wells (QWs) were sequentially grown in the same active region. Well-separated, blue-dominant dual wavelength emission was obtained by tuning the QWs stack [11].

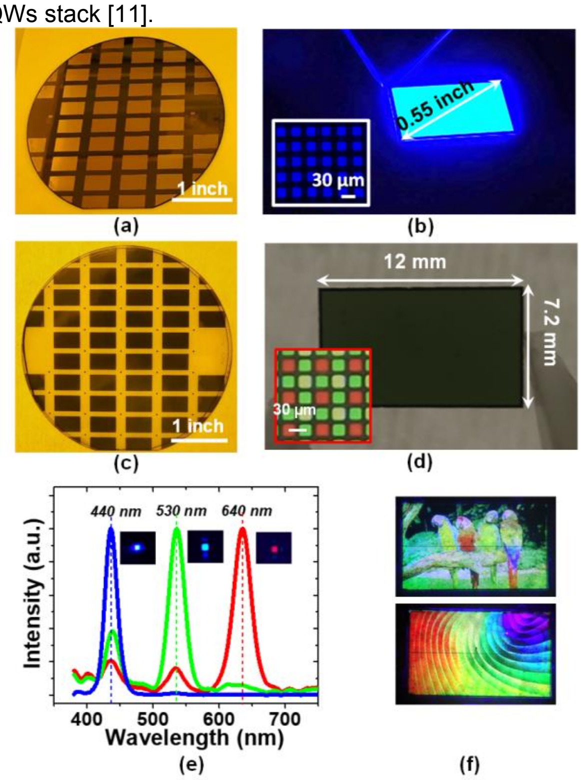

Fig. 3 (a) 4-inch GaN-on-Si wafer after the micro-LED fabrication. (b) Image of the 400 × 240 blue micro-LED chip with input current of 100 mA, inset is a zoomed-in image of the display area. (c) 4-inch transparent substrate after the color conversion layer fabrication. (d) Image of one die of the conversion layer, inset is a zoomed-in image of the color conversion layer. (e) EL spectra of red, green and blue subpixels. (f) 200 × 120 full-color images rendered on this micro-display.

Fig. 4 (a) shows the first option of achieving full-color micro-display using dual wavelength LED epilayers. A micro-LED array with blue/green dual wavelength emission was monolithically fabricated, in which the blue and green subpixels were easily defined by coating blue and green color filters (CF) onto different subpixels, respectively. Overcoat photoresist was utilized to planarize the micro-LED array, playing a role of passivation (PA) at the same time. Then red QDPR and CF were patterned on red subpixels. 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. Fig. 4 (b) demonstrates EL spectra of red, green and blue subpixels of this micro-display. The peak wavelength of RGB subpixels were 621 nm, 524 nm and 445 nm respectively. As shown in Fig. 4 (c), RGB bars with 8 different grayscale levels are displayed on this micro-display. A few defected lines were observed on the display panel, which can be eliminated by precise process control.

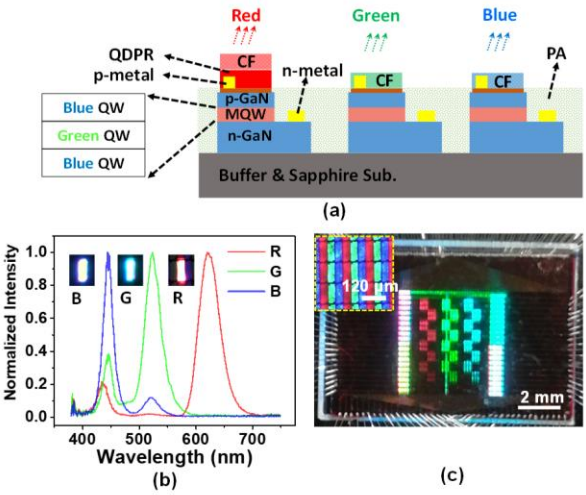

Fig. 4 (a) Schematic of the full-color micro-display using dual wavelength LED and red QDPR. (b) EL spectra of red, green and blue subpixels. (c) Full-color images rendered on this micro-display.

The second option is to flip-chip bond red AlGaInP micro-LEDs on the dual wavelength micro-LED array. Fig. 5 (a) illustrates the simplified structure of this micro-display. To start with, blue and green sub-pixels were defined monolithically on the dual wavelength LED epi-wafers. In the area of red sub-pixels, the active epilayers were etched away for the bonding of red micro-LEDs. In parrallel, a red micro-LED array was fabricated with a complementary structure using AlGaInP-on-GaAs epi-wafers [12]. Then the two arrays were integrated through Au/In flip-chip bonding. After wet etching of the opaque GaAs substrate, both red and blue/green micro-LEDs were exposed smoothly without damage (Fig. 5 (b)). The resolution of the integrated micro-display is 32 × 32 pixels with 120 μm pixel pitch. Fig. 5 (c) plots the EL spectra of red, green and blue sub-pixels, respectively. Some full-color images were displayed on this micro-display, as shown in Fig. 5 (d).

3 CONCLUSIONS

To conclude, multiple monolithic approaches to demonstrate micro-LED full-color micro-display are explored using different LED epi-wafers. Based on large-scale and low-cost GaN-on-Si blue LED epilayers and red/green CdSe/ZnS QDPR, 32 × 18 and a 400 × 240 micro-LED full-color micro-displays were established, respectively. Benefiting from the novel dual wavelength LED structure, both red QDPR and red AlGaInP micro-LED can be combined with dual wavelength micro-LED array to achieve full-color micro-displays. To emphasize, for all these monolithic approaches, it is feasible to scale down the pixel size while scaling up the processed wafer size, suggesting the great potential towards mass production of micro-LED full-color micro-display.

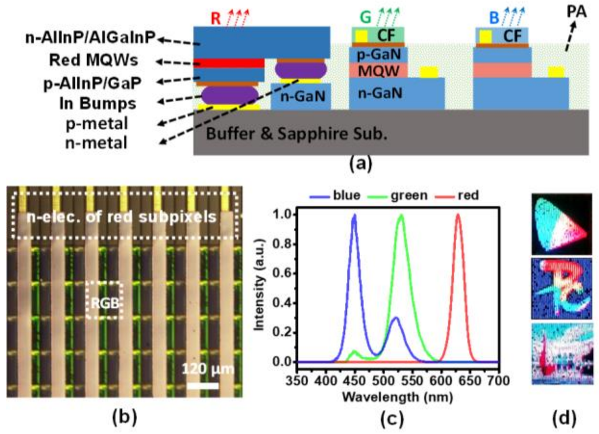

Fig. 5 (a) Schematic of the full-color micro-display using dual wavelength LED and red AlGaInP micro-LEDs. (b) Image of the display after GaAs substrate removal. (c) EL spectra of red, green and blue subpixels. (d) Full-color images rendered on this micro-display.

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