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SPECIAL SECTION PAPER

Active matrix monolithic micro-LED full-color microdisplay

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1 | INTRODUCTION

Micro-display technology, driven by various applications such as augmented reality (AR), virtual reality (VR), and wearable devices,^{1,2} has attracted rapidly growing interest. GaN-based micro-LED is one of the most promising candidates for the next-generation micro-display due to its superior properties including high brightness, long lifespan, and low power consumption, compared with other existing display technologies.^{3,4}

Remarkable results of high-performance monochromatic micro-LED micro-displays have been developed in both academia^{5,6} and industry^{7,8} since nearly a decade ago. However, full-color emission based on either various GaN epilayers or combined different semiconductors remains intrinsically challenging. The prevailing method to realize micro-LED full-color micro-display applies mass transfer technology^{9,10} in which red, green, and blue LED chips are selected from separate semiconductor wafers then assembled on the same display panel. Nevertheless, the equipment cost and transfer yield become issues as the pixel size scales down.

Alternatively, with potential process scalability, monochromatic micro-LED micro-displays with

Abstract

An active matrix monolithic micro-LED full-color micro-display with a pixel density of 317 ppi is demonstrated. Starting from large-scale and low-cost GaN-on-Si epilayers, monolithic 64×36 blue micro-LED arrays are fabricated and further transformed to full-color micro-displays by applying a photopatternable color conversion layer. This full-color fabrication scheme shows feasible manufacturability, suggesting a potential for volume production of micro-LED full-color micro-display.

K E Y W O R D S

active matrix, full-color, GaN-on-Si, micro-display, micro-LED, monolithic

extremely high pixel density can be fabricated monolithically and extended to full-color displays using color down conversion technology. Highly-emissive CdSe/ZnS quantum dots (QDs) have been adopted to convert desirable colors from monochromatic micro-LEDs.^{11,12} We and other researchers have reported full-color micro-displays by jet printing of red, green, and blue QDs on a monolithically fabricated UV micro-LED array.^{13,14} Although the jet printing technology offers a flexible process for QDs layer deposition, the QDs tend to spread easily because of the low-viscosity of the organic solvent, leading to insufficient light color conversion and unsatisfactory full-color display quality. Moreover, the production efficiency will be much limited especially for high-resolution microdisplays as the jet printing process requires a precise operation for each pixel.

Instead of jet printing, it is feasible to apply a mixture of QDs pristine solution with photoresist (QDs-PR), followed by patterning of the mixed QDs-PR using standard photolithography process, leading to efficient and large-scale manufacturability. Recently, fine-patternable QDs-PR has been synthesized and investigated.^{15,16} Sharp Corporation has demonstrated a 1053 ppi full-color micro-display using QDs-PR and a monolithic blue

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micro-LED array.¹⁷ GaN-on-sapphire epilayers were utilized in Sharp's demonstration, whereas the sapphire substrate was removed by laser lift-off process (LLO) before the QDs-PR patterning on the micro-LEDs array. Compared with sapphire, large-scale Si growth substrates provide high production efficiency and low cost.¹⁸ On the other hand, the Si substrate can be easily removed using a standard dry or wet etching processes. Multiple micro-LED micro-displays have been successfully developed using GaN-on-Si epilayers.^{19,20}

In this work, we report demonstration of an active matrix (AM) monolithic micro-LED full-color microdisplay combining GaN-on-Si epilayers and QDs-PR color conversion technology. First, a 64×36 blue micro-LED array, with a pitch size of 40 µm, was fabricated using GaN-on-Si epilayers. After integrating the blue micro-LED array with an AM CMOS backplane through a costeffective Cu/Sn-based bonding scheme, the Si growth substrate was removed by a simple SF₆-based reactive ion etching (RIE) process to expose the display area. Red and green QDs-PRs were independently patterned on a piece of thin glass to form a color conversion layer following the Bayer matrix (RGGB) configuration. The color conversion layer was then flip-chip bonded onto the exposed display area of the micro-LED array to achieve a fullcolor micro-display.

2 **EXPERIMENT**

2.1 | Blue micro-LED array

The GaN blue LED epilayers were grown on a 6-inch Si(111) substrate by metal organic chemical vapor deposition (MOCVD). The epilayers include a 1.2-µm-thick graded AlGaN buffer layer, a 0.5-µm-thick undoped GaN layer, a 2-µm-thick Si-doped n-type GaN layer, 10 pairs of InGaN/GaN multiple quantum wells (MQWs), and a 0.2-µm-thick Mg-doped p-type GaN layer in sequence.²¹

Figure 1A depicts the schematic of the blue micro-LED array, in which the common n-type electrodes are arranged in the peripheral region while the separate micro-LED p-contacts in the middle area. The fabrication procedures of this µLED array proceeds as follows: first, a layer of 115-nm-thick indium tin oxide (ITO) was deposited on the p-GaN layer by e-beam evaporation and patterned by wet etching in diluted aqua regia using photoresist mask. Then, the photoresist mask was reused to define the individual micro-LEDs by dry etching the GaN down to the n-GaN layer. After annealing the ITO layer to form an ohmic contact to the p-GaN, Cr/Al-based metal stack was deposited on top of the annealed ITO and n-GaN layer as p- and n-electrodes, respectively.

Next, the wafer was passivated by depositing a layer of SiO₂ using plasma enhanced chemical vapor deposition (PECVD), leaving opened holes on p- and n-electrodes. The Cu/Sn soldering bumps are formed on each micro-LED pixel and n-type electrode, independently using a two-step electroplating process.¹⁹ The detailed information of the layers from top to bottom are listed in Figure 1B. As shown in Figure 1C, the fabricated micro-LED array chip measures 1.60×2.72 mm, consisting of 64×36 pixels with a pitch size of 40 μ m and a density of 635 pixels per inch (ppi). Figure 1D displays the electroplated Cu/Sn bumps on the micro-LED array.

The CMOS backplane, consisting of 64×36 pixel drivers, a scan driver, a data driver and a hybrid voltage regulator, was fabricated using a commercial 0.18-µm bulk CMOS process. The voltage regulator is designed for the step-up and step-down voltage conversion to overcome the voltage fluctuation of the battery. The CMOS backplane was capable to provide an input range from 2.7 to 4.2 V and a maximum output power of 216 mW. The design details were illustrated in our previous publication.²² After depositing an additional bilayer of Ti/Cu (100 nm/1 μ m) on the pads of the CMOS backplane, the blue micro-LED array was flip-chip bonded on the backplane, and then, the Si growth substrate was removed by a SF₆-based RIE process, as shown in Figure 2A. Figure 2B,C shows the integrated chip before and after the Si growth substrate removal, respectively. Smooth and crack-free GaN layers were exposed in micro-LED display regions.

2.2 | Color conversion layer using QDs-PR

In this work, commercial red and green CdSe/ZnS QDs dispersed in toluene (50 mg/ml) were mixed with a highly transparent negative photoresist to synthesize fine-patternable red and green QDs-PR, respectively. After characterizing the conversion properties of the QDs-PR, a color conversion layer using QDs-PR was formed on a piece of 150-µm-thick glass. The color conversion layer and the blue micro-LED chip could be fabricated in parallel, offering potential to shorten the manufacturing cycle and improve the production yield. The process flow is illustrated in Figure 3. First, as shown in Figure 3A, a layer of commercially-available black matrix (BM) photoresist is patterned on the glass with a thickness of 5 µm using lithography process, to define the pixels and isolate the QDs-PR patterns. Then, the red and green color filters (CFs), also commercially available photoresists, are patterned in red and green subpixels with a thickness of 1.5 µm, following the Bayer matrix (RGGB) configuration (Figure 3B). After



FIGURE 2 (A) Schematic of the blue GaN micro-LED array integrated with the CMOS backplane. The integrated chip (B) before and (C) after the Si growth substrate removal



FIGURE 3 Process flow of the color conversion layer using quantum dots photoresist (QDs-PR)

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hard baking of the BM and CFs, multilayers of red and green QDs-PR are spin-coated on the glass with the target thickness of 10 μ m and then patterned following the same configuration (Figure 3C). Each layer of the patterned QDs-PR is cured under UV light illumination before coating of the next layer; thus, the QDs will be protected in the cured PR from the following lithography steps. To further suppress the crosstalk between the QDs-PR patterns, a second layer of BM was added with the same patterning as the first layer (Figure 3D). With a thin layer of UV epoxy coated on top, the color conversion layer on glass is flip-chip bonded on the integrated blue LED chip to demonstrate a full-color micro-display (Figure 3E).

3 | CHARACTERIZATION AND DISCUSSION

3.1 | Blue micro-LED array

Figure 4A demonstrates the *I*-*V* characteristic of a single pixel that is measured after the blue micro-LED array fabrication, showing a forward voltage of 2.8 V at 30 µA and a reverse leakage current less than 5 pA at -5 V. The light emission peak of blue micro-LEDs centers at 450 nm, which is determined by the starting epilayers. As shown in the emitting image of a single micro-LED, slight crosstalk still exists as the micro-LED array features a common n-GaN layer. To suppress this crosstalk, isolation of the n-GaN layer for each pixel is required to block the light scattering through n-GaN layer in the future work. After hybridizing the blue micro-LED array and the CMOS backplane, a blue micro-display system is established by connecting the hybridized LED chip to an Arduino DUE board. Images and video in resolution of 64×36 are clearly rendered under a 4-bit grayscale control, as shown in Figure 4B, implying a high bonding yield of the Cu/Sn-based bonding scheme.

3.2 | QDs-PR preparation and characterization

Typically, the surface of QDs is bound by organic surfactants, also known as ligands (e.g., carboxylates), which mediate their crystallization and maintain their colloidal dispersion in organic solvents such as toluene, chloroform, and hexane. The surface-bound ligands of QDs are not perfectly compatible with the typical photoresists, making it difficult to disperse solid QDs directly in photoresist. However, it is still possible to disperse QDs stably in photoresist if the QDs pristine solution (e.g., QDs in toluene) is mixed with the photoresist at an appropriate volume ratio. In this demonstration, CdSe/ZnS QDs dispersed in toluene (50 mg/ml) were applied, with the emission peak wavelength locates at 540 nm for green QDs while 650 nm for red QDs. A type of negative overcoat photoresist (Product no. EOC130) was utilized due to the high transparency and resolution. The mixing ratios of the QDs pristine solution to the photoresist were optimized at 3:2 to get stably dispersed red QDs-PR. The optimized ratio for green QDs-PR was slightly higher (2:1), possibly due to the smaller size of green QDs. The average particle size of green QDs is determined as 10 nm by the supplier, whereas that of red ones is 15 nm.

Considering the low viscosity of the QDs pristine solution, the optimized QDs-PR was spin coated on wafers at a slow spin speed (200 rpm) for a long duration (120 s), leading to a thickness of 2.7 μ m. Tunable thickness of the spin-coated QDs-PR can be easily achieved by adjusting the spin speed. Moreover, much thicker QDs-PR (>10 μ m) will be available if multilayers spin-coating applied. Due to the degradation of QDs at high temperature, the soft baking of QDs-PR was performed at 55°C for 5 min. After the UV exposure and developing in KOH-based solution, the QDs-PR was finely patterned. Figure 5A–B exhibits the fine patterns of the 2.7- μ m-thick red and green QDs-PR, respectively, indicating high-resolution photosensitive performance of the QDs-PR.





FIGURE 4 (A) *I–V* curve of a single micro-LED, insets are the electroluminescence spectra and the emitting image. (B) Images rendered on the blue micro-display system





To estimate the conversion properties, the QDs-PR was spin-coated on a piece of 150-µm-thick glass. After soft baking and UV curing of the whole layer, the QDs-PR on glass was excited by applying a blue backlit LED closely to the backside of the glass. The blue backlit LED, circular in shape with a diameter of 320 $\mu m,$ was fabricated using the same GaN epilayers. The blue light would penetrate the glass and QDs-PR layer successively allowing the unabsorbed blue light together with the converted red or green light to be collected by an integrating sphere. Based on the obtained spectra, the light output powers of the unabsorbed blue light (P_{B1}) and the converted red (P_{R1}) or green (P_{G1}) light can be calculated by integrating the power distribution across the corresponding wavelength intervals, respectively. The integrating intervals for blue, green, and red light power are 400-480, 500-580, and 600-700 nm, independently. A piece of bare glass was illuminated in the same setup as a reference to estimate the total blue light output power (P_{B0}) that passed through the thin glass and the QDs-PR layer. Thus, the absorption ratio, conversion ratio, and power conversion efficiency (PCE) can be defined as follows:

Absorption Ratio =
$$\frac{P_{B0} - P_{B1}}{P_{B0}}$$
 (1)

Conversion Ratio =
$$\frac{P_{R1}}{P_{B0} - P_{B1}}$$
 (Red) or $\frac{P_{G1}}{P_{B0} - P_{B1}}$ (Green)
(2)

Power Conversion Efficiency = $\frac{P_{R1}}{P_{B0}}$ (Red) or $\frac{P_{G1}}{P_{B0}}$ (Green) (3)

The conversion properties of the red QDs-PR are presented in Figure 6. Three samples were measured and compared, with the red QDs-PR layer thickness of 1, 5, and 10 μ m, independently. As shown in Figure 6A, with the backlit LED injected at 150 mA, both absorption and conversion ratios increase with the rise of the red QDsPR layer thickness. The 1-µm-thick red QDs-PR layer delivers an absorption ratio of 35% and a conversion ratio of 6%, whereas the two values of the 10-µm-thick layer reach up to 85% and 12%, respectively. As a result, the 10-µm-thick red QDs-PR layer exhibits a much higher PCE of 10%, compared with the 1- and 5-µm-thick layers (Figure 6B). At different input currents of the backlit LED, the PCE remains steady for the same red QDs-PR layer, implying the conversion stability of the red QDs-PR layer at different illuminating powers. Figure 6C depicts the spectra of the converted red light ($\lambda \sim 655$ nm) together with the unabsorbed blue light ($\lambda \sim 440$ nm) from the red QDs-PR layers when illuminated by the backlit LED at an input current of 150 mA. For 10-µmthick red QDs-PR layer, the unabsorbed blue light was still stronger than the converted red light. Therefore, it is indispensable to apply an additional layer of red CF to block the unabsorbed blue light in the actual full-color demonstration.

Unlike the red QDs-PR, the conversion properties of green QDs-PR prove to be much weaker even for 10-µmthick layer. To enhance the conversion properties, the green QDs-PR was modified by blending silica nanospheres (~20 nm in diameter) at an optimized concentration of 25 mg/ml. As shown in Figure 7A, the absorption ratio of the 10-µm-thick green modified QDs-PR (MQDs-PR) increases by over 40% at all input currents of the backlit LED, compared with that of the original QDs-PR. This improvement mainly attributes to the enhanced light scattering in the MQDs-PR due to the silica nanospheres blending.²³ On the other hand, the conversion ratio is only slightly improved, which is mainly determined by the QDs intrinsic property. In total, with the backlit LED injected at 150 mA, the PCE of the 10-µm-thick green MQDs-PR layer jumped to 6.8%, from 3.7% of the original layer without modification (Figure 7B). The spectra in Figure 7C manifests an enhanced green light conversion (λ \sim 540 nm) of the MQDs-PR, whereas a large proportion of the blue light remains unabsorbed. Thus, it is also essential to add a layer of green CF to eliminate the unabsorbed blue light.



FIGURE 6 (A) Absorption/conversion ratios of the red quantum dots photoresist (QDs-PR) layers with different thicknesses when illuminated by the blue backlit LED at an input current of 150 mA. (B) Power conversion efficiencies of the red QDs-PR layers with the backlit LED injected at different currents. (C) Spectra of the converted red light together with the unabsorbed blue light from the red QDs-PR layers with different thicknesses when illuminated by the blue backlit LED at an input current of 150 mA.



FIGURE 7 (A) Absorption/conversion ratios and (B) Power conversion efficiencies of the 10-µm-thick green quantum dots photoresist (QDs-PR) and modified QDs-PR (MQDs-PR) layers when illuminated by the blue backlit LED at different input currents. (C) Spectra of the converted green light together with the unabsorbed blue light from the 10-µm-thick green QDs-PR and MQDs-PR layers when illuminated by the blue backlit LED at an input current of 150 mA, respectively

To note, it is infeasible to further enhance the absorption ratio of the green MQDs-PR by increasing the concentration of the silica nanospheres, because the resolution of the MQDs-PR degrades with the rising composition of the nanospheres. Although evident enhancement of light conversion was observed for green MQDs-PR with silica nanospheres blending, it is hardly inevitable to modify the red QDs-PR using the same method. As the absorption ratio of 10- μ m-thick red QDs-PR has reached up to 85%, which implies the light scattering is strong enough due to the relatively larger size of red QDs.

Figure 8 displays the inspection images during the color conversion layer fabrication. As shown in Figure 8A, the BM opening hole is in size of $30 \times 30 \ \mu\text{m}$, whereas the red/green CFs patterns match the opening holes well. In Figure 8B, the 10- μ m-thick red QDs-PR and green MQDs-PR are finely patterned into squares in size of $23 \times 23 \ \mu\text{m}$. Rough surface is observed for the green MQDs-PR due to the silica nanospheres blending. After the second layer BM

patterning (Figure 8C), the sidewall of QDs-PR patterns are fully covered by the overall BM to suppress the light crosstalk. Figure 8D demonstrates the image of the 150- μ m-thick thin glass wafer after all the photoli-thography processes, in which each die consists of 64 × 36 subpixels corresponding to the layout of the blue micro-LED array (Figure 8E).

3.3 | Full-color micro-display

After flip-chip bonding the color conversion layer on the blue micro-LED chip, the blue micro-display is easily transformed to a 32×18 full-color micro-display with a pitch size of $80 \times 80 \ \mu\text{m}$ and a pixel density of 317 ppi. Figure 9A shows the final top-down view of the full-color micro-display chip. Figure 9B presents a zoomed-in image of the flipped color conversion layer, in which the BM and CFs patterns are clearly observed through the thin glass.



FIGURE 8 Inspection images during the color conversion layer fabrication. (A) After the first layer BM and red/green CFs patterning. (B) After the red QDs-PR and green MQDs-PR patterning. (C) After the second layer BM patterning. (D) One piece of the thin glass wafer after all the photolithography processes. (E) One die of the color conversion layer



FIGURE 10 (A) Electroluminescence (EL) spectra when red, green, and blue subpixels are powered on, independently. The insets are the corresponding displayed images. (B) The color gamut of this micro-display and sRGB in CIE 1931 chromaticity diagram. (C) Full-color images rendered on this full-color micro-display system

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Driven by the same Arduino DUE control board, a full-color micro-display system is demonstrated. The electroluminescence (EL) spectra are analyzed for each primary color rendered on this full-color micro-display system, as shown in Figure 10A. No color shift of the blue emission is observed after the Si growth substrate removal, with the peak wavelength remained at 440 nm. Dominant red and green light emissions are obtained for red and green subpixels, respectively, indicating sufficient color conversion and suppressed light crosstalk. Figure 10B plots the color gamut of this full-color microdisplay in the CIE 1931 chromaticity diagram, covering 70% of the sRGB color space. Figure 10C demonstrates two full-color images displayed on this system. It is strongly believed that both the red and green light conversions can be enhanced with improved QDs-PR. The long-term stability of the QDs-PR patterns will be investigated in future work.

4 | CONCLUSION

To conclude, an AM monolithic full-color LED microdisplay was demonstrated, combining the large-scale and low-cost GaN-on-Si epilayers together with a lithography-based QDs-PR patterning method. First, a 64×36 blue micro-LED array, with a pitch size of 40 µm, was monolithically fabricated using GaN-on-Si epilayers. After hybridizing this blue micro-LED array with an AM CMOS backplane through a cost-effective Cu/Sn-based bonding scheme, the Si growth substrate was removed by a dry etching process to expose the display area. The QDs-PR was synthesized and optimized by mixing the QDs pristine solution with a commercially available negative photoresist in appropriate volume proportions. Green QDs-PR was modified with silica nanospheres blended. The red QDs-PR and green MQDs-PR present high-resolution performance in photolithography process even with a thickness of 10 µm. The PCE of the 10-µm-thick red QDs-PR and green MQDs-PR was estimated to be 10% and 6.8%, respectively. A color conversion layer following the Bayer matrix (RGGB) configuration was formed on a piece of thin glass by patterning the BM, CF, and QDs-PR step by step. After flip-chip bonding the color conversion layer on the blue micro-LED chip, a fullcolor micro-display is achieved, featuring a resolution of 32 \times 18, a pitch size of 80 \times 80 μ m and a pixel density of 317 ppi. This methodology exhibits feasible manufacturability and full-color display capability, suggesting a tremendous potential for volume production of micro-LED full-color micro-display in the near future.

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