Monolithic Full-color LED Micro-display Using Dual Wavelength LED Epi-layers

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ABSTRACT

A passive-matrix InGaN LED full-color micro-display with 40 × 40 pixels (120 × 40 RGB subpixels) and subpixel pitch of 40 µm × 120 µm was demonstrated. Full-color emission was realized by applying patterned red quantum dot color conversion layer onto a monolithic blue/green dual wavelength LED array.

1 INTRODUCTION

InGaN-based light emitting diode (LED) micro-display has been extensively explored as a promising candidate for virtual reality, augmented reality and wearable electronics. Compared to liquid crystal display (LCD) and organic light emitting diode (OLED) display, it features higher brightness, superior stability and long lifetime. However, production-friendly approaches to achieve full-color emission on LED micro-display panels have not been well-developed.

Attempts aiming at full-color technologies have been conducted over the past few years. The industry has been putting in great efforts in developing mass-transfer technologies to place individual color LED pixels on the display. However, the starting epi-wafer and fabrication process of blue/green InGaN LEDs and red AlGaInP LEDs are significantly different. Furthermore, it is inherently a high-cost process to achieve good yield as the pixel size scales down and the number of pixels to be transferred increases.

Monolithic fabrication, which means full-color pixels are directly fabricated on the same epi-wafer, is an alternative approach. Because of the typical monochromatic emission properties of InGaN-based material, special structures and techniques need to be proposed. For example, InGaN quantum wires were grown by molecular beam epitaxy (MBE) to obtain emission covering the full range of visible spectrum [1]. Strain-induced wavelength shift of InGaN-based nanopillar LEDs was also reported [2]. However, these approaches are yet to be satisfactory in the aspects of efficiency, yield and reproducibility. It has not been proven practical to extend such research results into high-volume production of full-color micro-display in the near future.

Color conversion technology provides another method for realizing monolithic full-color micro-display, which has potential to overcome those drawbacks. The conversion technology has been demonstrated in phosphor-based white light generation in LED lighting for more than one decade. Among various kinds of color convertors, colloidal quantum dot (QD) is the most ideal color convertor for full-color micro-displays due to its high quantum yield and wide color gamut. But research has indicated its conversion efficiency issues, especially for blue (excited by UV-A) and green QDs (excited by blue visible light). The excitation wavelength is not short enough to match the absorption spectra of QDs [3]. Moreover, tuning the thickness of the QD layer is tricky: It should be thick enough for sufficient down-conversion of excitation light but not too thick to maintain the resolution of QD patterns. For instance, the representative state-of-the-art technology for QD patterning process, jet printing, can only deposit QD film no more than hundreds of nanometer thick with limited QD optical density, leading to unfavorable performance of the full-color micro-display [3].

We have developed a new QD-based monolithic fabrication approach to overcome the above-mentioned technical difficulties. Blue/green dual wavelength InGaN LED epi-layers were grown on sapphire substrates and monolithically fabricated to be a passive-matrix driven micro-LED array. Red QD photoresist made of highly-transparent photoresist and QD pristine solution, was patterned as a color conversion layer on the red subpixels. The thickness of the QD layer could be adjusted in the order of micrometers, providing sufficient light absorption and down-conversion. RGB color filters (CFs) were patterned as well on corresponding subpixels to filter undesired color components. This novel manufacturing technology presents relatively wide color gamut, acceptable color conversion efficiency and potential high yield.

2 EXPERIMENT

Dual wavelength emission of LED and red light generation from QD color conversion layers are two main challenges for the proposed full-color micro-display. The fabrication process of the micro-display will be described in this section, including the discussion of dual wavelength LED epi-layers and full-color realization.

2.1 Structure of Dual Wavelength LED Epi-layers

The dual wavelength InGaN LED epi-layers were grown on a 2-inch c-plane sapphire substrate by metal-organic chemical vapor deposition (MOCVD). The typical structure (Fig. 1(a)) includes one green quantum well (QW) sandwiched between one blue QW on top and three blue QWs underneath for dual wavelength emission. The growth sequence of QWs aims to achieve a blue peak dominant dual wavelength LED since the radiative recombination in the green QW is believed to be suppressed by the capping blue QW. Blue-dominant dual wavelength LEDs are more suitable for display applications, not only for the enhancement of conversion efficiency for the red QDs, but also for the high sensitivity of human eyes to green. The luminous intensity of blue or green LEDs are presumably easier to be balanced considering the eye sensitivity function.

The performance of the dual wavelength structure was confirmed on circular mesa-structure LEDs with a diameter of 320 μm. (Fig. 1(b) inset) The electroluminescence (EL) spectra were characterized inside an integrating sphere. Blue-dominant, well-separated blue emission at 460 nm and green emission at 539 nm were clearly observed under 20 mA injection current and the trend stayed the same at all measurement current (from 1 mA to 100 mA). (Fig. 1(b)) The total light output power was 2.20 mW at 20 mA.

2.2 Fabrication of LED Array

The monolithic passive-matrix InGaN LED full-color micro-display was fabricated directly on the dual wavelength epi-layers without any transfer or bonding process. 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. The schematic cross-section of a full-color pixel is illustrated in Fig. 2(a) and the top view is shown in Fig. 2(b) with the dimensions of the pixel.

In the micro-display fabrication process, isolation trenches were first formed among subpixels by BCl_3/Cl_2 dry etch using silicon dioxide as an etching mask. The trenches were etched down to the sapphire substrate for complete electrical isolation. A self-aligned process was then performed to pattern indium tin oxide (ITO) and etching mesa under the same photoresist mask, preventing possible misalignment. In this process, ITO was wet etched in the diluted aqua regia and 1 μm mesa structure was formed using the similar BCl_3/Cl_2 dry etch afterwards. A multilayer metal electrode, Ti/Al/Ti/Au, was deposited by e-beam evaporation as cathodes connected to the exposed n-GaN. Ti/Cu based 3 μm-thick metal wires were sputtered for anodes. Such thick anodes required 10 μm-thick photoresist AZ4620 as a lift-off mask. Subpixels were designed to have common anodes in each row and common cathodes in each column. Due to our row scan driving scheme, the current of all 120 subpixels would passed through the same anode. It is the reason that Ti/Cu anodes must be thick enough for lower resistance to reduce voltage drop along the metal contact line. Transparent overcoat photoresist EOC-130 was deposited as a passivation and insulation layer before depositing each metal layer, only leaving contact vias for electrodes and cavities for red QD. The EOC layers were cured after hard baking, becoming chemically inert towards most kinds of etchant and organic solvent.

2.3 Full-color Realization

QD patterning and CF coating processes were conducted after the formation of the LED array. Prior to the QD patterning process, blue and green CFs were patterned on the corresponding subpixels for realizing pure blue and green emission. The photo taken before QD patterning is given in Fig. 3(a). 2.5 μm-deep cavities formed by EOC on red subpixels were also shown in the photo, which were designed to contain thick QD. After blue/green CF coating, QD photoresist was applied as a color conversion layer to generate red light. The red CdSe/ZnS QDs emitting at 630 nm were dispersed in toluene (~150 mg/mL), provided by our collaborators. The QD-toluene dispersion was mixed with EOC-130 at the volume ratio of 1:2 (QD:EOC) under ultra-sonication. The QD photoresist was patterned similar to that of the EOC passivation except for the higher exposure dose because of the UV absorption of QD. Due to the surface planarization properties of photoresist, the cavities were fully filled with QD photoresist where the thickness was thick enough for efficient color conversion. Fig. 3(b) shows the photo after the QD patterning process. The dark regions on the red subpixels were deposited QD, which had been uniformly patterned without any deformation and residues after developing. Although the QD conversion layer had strong absorption and light scattering, there were still unabsorbed blue/green components that leaked from the top. To solve the problem, red CF was also coated on the QD patterns. The completely fabricated RGB subpixels are illustrated in Fig. 3(c), which demonstrates a simple RGB stripe arrangement. Finally, the backside of the substrate was coated with thick red CF (>10 μm). The backside coating layer was used for suppressing light guiding phenomenon in the transparent sapphire substrate as much as possible [4]. There would be poor color mixing performance without this layer because of severe optical crosstalk among subpixels, especially for red emission.

3 RESULTS

The full-color micro-display was characterized and demonstrated. Single subpixel was lit up and photographed on the probe station to provide an intuitive view of light emission. Fig. 4(a) are the photos of RGB subpixels respectively taken at the constant current of 1 mA. The result showed acceptable color purity. It is especially extraordinary for red subpixels, since red emission converted by QD layers was relatively weak. Because of the absorption of backside CF coating, the optical crosstalk between adjacent subpixels was insignificant. Even though there was still QD excited at the edge of red subpixels when blue/green pixels were lit up, it did not affect much on the color purity.

In order to characterize quantitatively, EL spectra of the RGB subpixels at 1 mA were measured and are plotted in Fig. 4(b). The peak wavelength of RGB subpixels were 621 nm, 524 nm and 445 nm with full width at half maximum (FWHM) of 42 nm, 32 nm and 20 nm, respectively. The output power intensity was normalized in the figure to indicate that the remaining undesired color components only occupied less than 20 % of the total light output power with the existence of CFs. The remaining blue peak in the spectrum of red subpixels was blue-shifted, because the red CF have higher transmittance increasing from 450 nm to 390 nm. Therefore, the remaining blue peak shifted to shorter wavelength with smaller FWHM.

The monolithic full-color micro-display was driven by an Application Specific Integrated Circuit (ASIC) based RGB micro-display controller that had been published in [5] as a demo. Our controller had 6-bit grayscale (64 levels for each color) capability driven in RGB mode using pulse width modulation (PWM) technology. Each die of the display including peripheral bonding pads was 10.966 mm × 7.850 mm in dimensions and the panel region was a 4.800 mm × 4.800 mm square. The demo displayed RGB bars with eight different grayscale levels (Fig. 4(c)). Only few dead lines were on the display panel of which the yield was limited by our experiments and can be further improved.

4 CONCLUSIONS

A passive-matrix InGaN LED full-color micro-display was successfully demonstrated. Different from other approaches, the full-color micro-display was fabricated from blue/green dual wavelength InGaN LED epi-layers on sapphire, using red QD as a color convertor. Red QD photoresist made from QD solution and transparent overcoat photoresist EOC-130 could be patterned as a normal negative-type photoresist, forming a QD film array on red subpixels. The patterned QD film array had high efficiency for generating red light. Relatively pure RGB light were obtained from subpixels, and full-color demo patterns with grayscale changes were achieved using an ASIC-based micro-display controller. This new approach not only simplifies the process for QD color conversion full-color micro-display in contrast with other reported results using multiple kinds of QDs, but also improves the conversion efficiency of QD. Great potential in practical applications are expected in the future.

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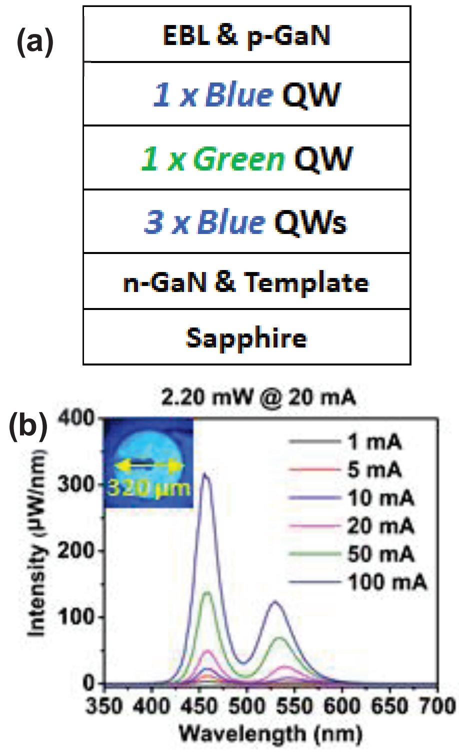

Fig. 1 Dual Wavelength LED
(a) Structure of the dual wavelength LED epi-layers. (b) EL spectra of the dual wavelength LED device. Measurement was performed on a 320 μm-diameter circular LED device (inset picture).

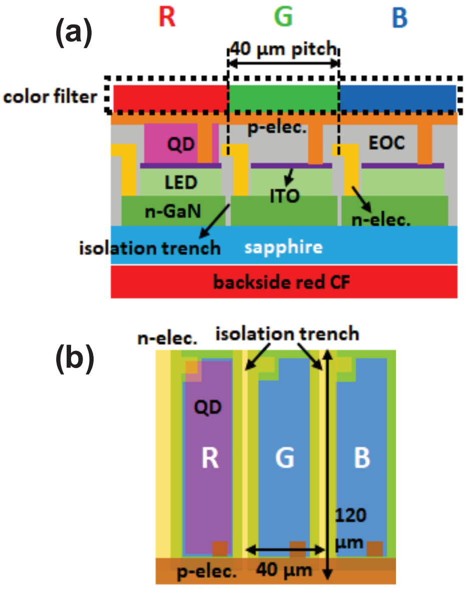

Fig. 2 Schematic view of RGB subpixels in the micro-display
(a) Cross-section of RGB subpixels. (b) Top view of RGB subpixels (EOC and CF are omitted).

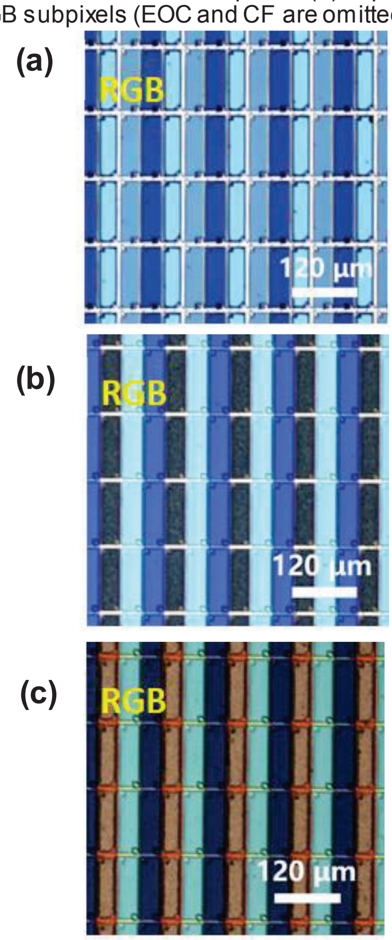

Fig. 3 Photos of QD and CF patterns
(a) Before QD and red CF were patterned. (b) QD patterns without red CF. (c) Subpixels with QD and CF.

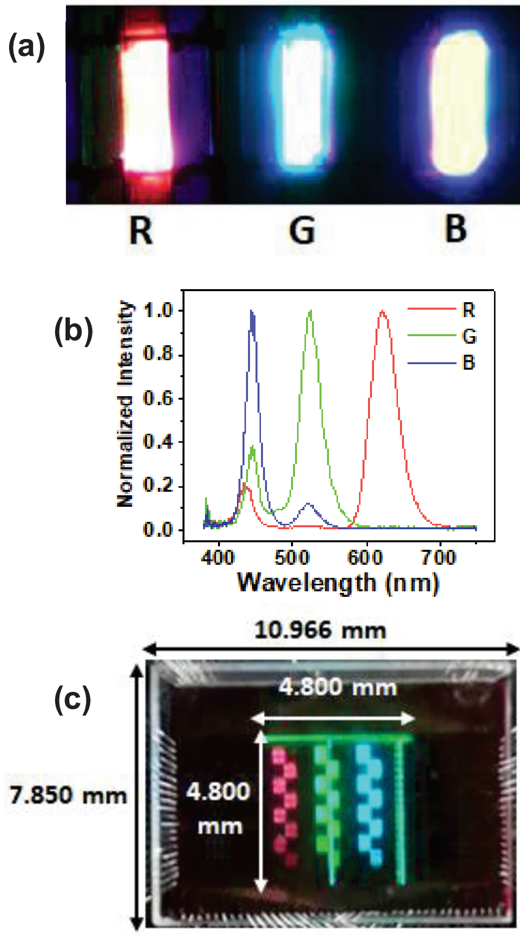

Fig. 4 Characterization of the full-color micro-display
(a) Photos of turned-on RGB subpixels at 1 mA. (b) Normalized EL spectra of RGB subpixels at 1 mA. (c) Full-color demo with 8-level grayscale.