Hybrid-integrated Monolithic Active-matrix Blue/Red Dual-color Micro-LED Micro-display

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ABSTRACT

A prototype of hybrid-integrated monolithic active-matrix blue/red dual-color micro-LED micro-display was demonstrated by flip-chip bonding of GaN-on-Si blue micro-LED array and AlGaInP red micro-LED array. This integration method is promising for high brightness, high color performance micro-LED micro-display application in the future.

1 Introduction

Micro-LED is deemed as the next generation display technology because of its superiorities in high brightness, long lifespan, low power consumption and fast response time compared with the existing mature OLED and liquid crystal display technology [1]. However, the development of micro-LED display technology is full of challenges, such as the size-dependent efficiency issue, complicated fabrication process and difficulty of full-color realization. Among all of these issues, realizing satisfied full-color emission is the most challenging and core issue to be solved for the practical application of micro-LED displays.

Generally, the technical routes for full-color realization of micro-LED displays can be divided into following two: the mass transfer method and monolithic growth/fabrication method. Mass transfer is to pick massive individual RGB micro-LED subpixels from separate epi-wafers and place them accurately onto the assigned positions of the backplane. This technology is suitable and preferred for displays which have a large pixel pitch and relatively low pixels per inch (ppi) such as smartphones, laptops and TVs. Monolithically growing RGB tri-color on single epi-wafers through strain engineering [2], nanowires [3] and cascaded active regions [4] are still under development due to their inapplicable low efficiency or complicated driving method for a practical display. Besides monolithic growth, the monolithic fabrication method is to combine the monolithically fabricated micro-LED arrays and color converting materials such as quantum dots (QDs) which have narrow spectra and high quantum yields to realize full-color emission [5]. The monolithically fabricated micro-LED array is very suitable for the micro-display application because of its chip-level fabrication, making high ppi display favorable to implement. The monolithic micro-LED display chip can be realized with the integration of the CMOS backplane using flip-chip bonding or by direct wafer level bonding. However, the brightness and color performance of QD-based full-color micro-LED micro-displays highly depend on the conversion and absorption efficiency of QD materials, which also need to be further improved to the meet the requirements of high-brightness and wide color gamut in micro-display applications such as projectors, augmented/virtual reality displays.

Here, we demonstrated a prototype of hybrid-integrated monolithic active-matrix blue/red dual-color micro-LED micro-display. Without using color conversion, high brightness and pure color are expected from this dual-color micro-display. The integration method is promising for the full-color micro-LED micro-display application.

2 Experiment

In this section, we briefly describe the fabrication process of the monolithic GaN-on-Si blue micro-LED array, AlGaInP red micro-LED array and the hybrid integration method, respectively.

2.1 Monolithically fabricated GaN-on-Si blue micro-LED array

The fabrication of blue micro-LED arrays starts with a GaN-on-Si LED epi-wafer. Firstly, the size of 30 μm x 30 μm window regions, which were left for the bonding of the monolithic red micro-LED array, were defined by the Cl_2/BCl_3 based inductively coupled plasma (ICP) etching. Then the mesa of blue micro-LED with a size of 15 μm was patterned using an ITO self-alignment process to avoid any current leakage issues caused by the misalignment. Cr/Al based metal stacks were deposited on ITO and n-GaN as p and n metal, respectively, as shown in Fig. 1(a). The sidewalls of etched window regions were passivated by a layer of SiO_2 to prevent short circuit of red pixels during the flip-chip bonding of the red micro-LED array. A transparent overcoat photoresist was then used to planarize the surface morphology of the micro-LED array. Contact holes were opened on the p and n bonding pad regions to help the reflow of Sn solder bumps. The inspection of micro-LED array after reflow was shown in Fig. 1(b), where the Sn micro-bumps on p and n bonding pads were 7 μm and 9 μm, respectively. Finally, the GaN-on-Si blue micro-LED array was flip-chip bonded onto a CMOS backplane, followed by Si growth substrate removal to allow the reflected blue light emitting from the bottom [6]. A 500 nm thin AlGaN buffer layer was intentionally kept during the etching process of window regions, acting as an etch stop layer during Si substrate removal.

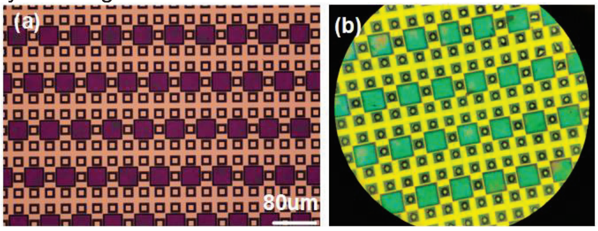


Fig. 1 After (a) p and n metal deposition and (b) Sn micro solder bumps reflow of the GaN-on-Si blue micro-LED array.

Fig. 2(a) clearly presents the exposed AlGaN buffer layer after the Si substrate removal of the monolithic integrated blue micro-LED display chip. The bonding pads on the CMOS driver under the window regions were patterned with a Ti/Au layer. To etch through this window regions, $SF_6/Cl_2/BCl_3$ mixed plasma was used to remove the above mentioned 500 nm thin AlGaN buffer layer by an etchback process. The etchback parameters are critical because aluminum composition is much higher in the bottom buffer layer. Inappropriate etching parameters will cause dense islands and dots, thus suspending the etching process. The etched-through window regions are displayed in Fig. 2(b). Up to this point, the blue micro-LED micro-display chip is well prepared for the flip-chip bonding of the AlGaInP red micro-LED array.

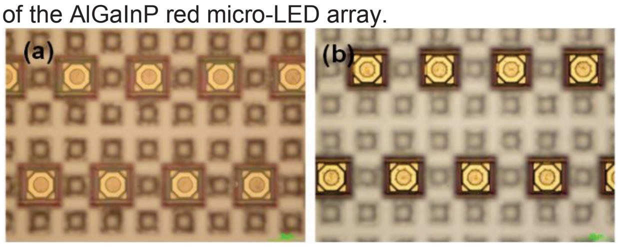


Fig. 2 (a) Si growth substrate removal. (b) Etchback of the thin AlGaN buffer layer.

2.2 Monolithically fabricated AlGaInP red micro-LED array

AlGaInP epi-wafers grown on the GaAs substrate were used for the fabrication of the red micro-LED array. Similarly, the window regions with a size of 50 μm x 50 μm were firstly defined by ICP etching. These window regions act as a light emission windows for the light emitting from the bottom blue micro-LED micro-display. Then Au was deposited and patterned as p metal using KI/I_2 mixed solution. The mesa etching of red micro-LED also adopts the self-aligned process. Subsequently, the remaining n-type AlGaInP layers in window regions were totally etched by wet etching using HCl/H_3PO_4 mixed solution. The annealed Ge/Au/Ni/Au metal stack was used as an n-metal layer (Fig. 3(a)). The large undercut of window regions was induced by the wet etching. Therefore, an appropriate ratio of mixed etchants and designed margins should be taken into account in the further process. A thick layer of SiO_2 was deposited over the whole micro-LED array and contact holes on p and n bonding pads were opened to assist solder metal reflow. SiO_2 also acts as an etch stop layer in the window regions during GaAs substrate removal. Later, thick BCB (3022-57) was over-coated to planarize the surface morphology and cured to increase the mechanical stability of the red micro-LED array. BCB etchback was performed to expose both of the p and n contact holes. Finally, indium (In) was patterned on the p and n contacts of red micro-LEDs and reflowed into micro solder bumps, which are 10 μm and 6 μm, respectively (Fig. 3(b)).

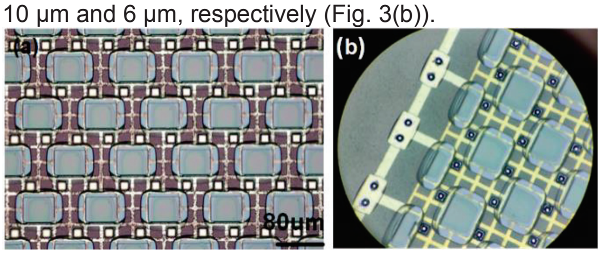


Fig. 3 After (a) p and n metal annealing and (b) In micro solder bumps reflow of the AlGaInP red micro-LED array.

2.3 Hybrid integration method

Through the window regions on the blue micro-LED array, the AlGaInP red micro-LED array was flip-chip bonded to the as-prepared blue micro-LED display chip. The adopted Au/In bonding of the red micro-LED array has lower soldering temperature than the Au/Sn bonding of blue GaN-on-Si blue micro-LED array so that it will not damage the as-bonded structures. With the under protection of silicone, the GaAs substrate was further removed using wet etching by ammonia/H_2O_2 mixed solution [7] because of the severe absorption of GaAs in the visible light range. Crack-free and smooth AlGaInP surface was exposed after the GaAs removal (Fig. 4). In this monolithic hybrid structure, the blue light emits from the window regions on AlGaInP red micro-LED array and red light emits from the window regions left for the bonding of red pixels on the blue micro-LED array. The SEM image shows the cross-section of the hybrid structure, in which the monolithic AlGaInP red micro-LED array was bonded to the blue GaN thin-film micro-LED display chip through the window regions.

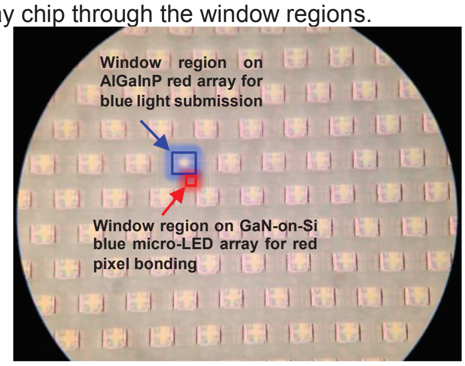


Fig. 4 After the hybrid integration and GaAs susbtrate removal.

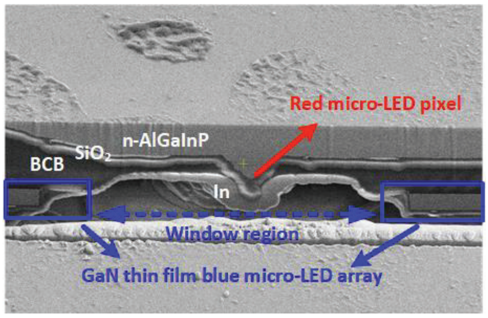
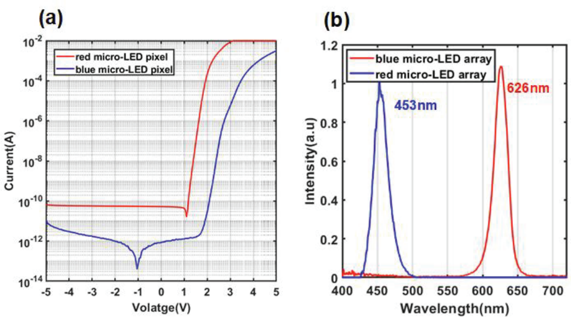


Fig. 5 Cross-section of the hybrid structure.

3 Results

Current-voltage (I-V) characteristics of the single blue and the red micro-LED pixel were measured (Fig. 6(a)). Both of the blue and the red micro-LED pixel show very low reverse leakage current and small series resistance. The leakage currents of red and blue micro-LEDs at -5 V are 65.2 pA and 9.5 pA, respectively. Extracted series resistances from the logarithmic I-V curves (<0.1 mA) are both less than 0.5 kΩ for blue and red micro-LEDs, which are attributed to the low ohmic contact resistance due to the metal electrode thermal annealing. In perspective of the behavior of a whole array, we turned on all the blue pixels of the GaN thin-film display as only 3-um thick GaN thin film was left after Si growth substrate removal. The peak of electroluminescence (EL) spectrum is located at 453 nm (Fig. 6(b)). Uniform emission of the blue pixels and high yield of the GaN thin-film display can be observed from Fig. 6(c) when giving a DC injection current of 50 mA. After the etchback of AlGaN buffer layer at window regions, uniform emission and yield are almost unchanged at the same 50 mA injection current (Fig. 6(d)). I-V characteristics of the whole array shown in Fig. 6(e) also prove that the critical AlGaN etchback process will not influence the electrical performance of this bonded GaN thin-film micro-LED display. Inspections of pixel view under microscope clearly identify emitting pixels and window regions (Fig. 6(f)).



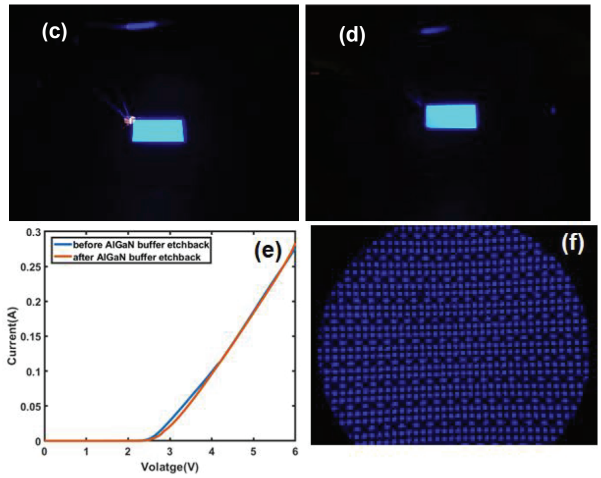


Fig. 6 (a) I-V curves of blue and red micro-LED pixel. (b) EL of blue and red micro-LED array. Display image (c) before and (d) after the etchback of AlGaN buffer layer. (e) I-V curve of the GaN thin-film micro-LED display. (f) Pixel view under microscope.

When all the red pixels were turned on, the EL peak of red emission was measured as 626 nm (Fig. 6(a)). A much stronger red emission was observed compared with the blue emission when giving the same injection current (Fig. 7(a)). This is because red micro-LED pixels have lower forward voltages than the blue micro-LED pixels so that the driving current for the red is much easier to be saturated. The yield of AlGaInP red pixels is very high after the GaAs substrate removal (Fig. 7(b)).

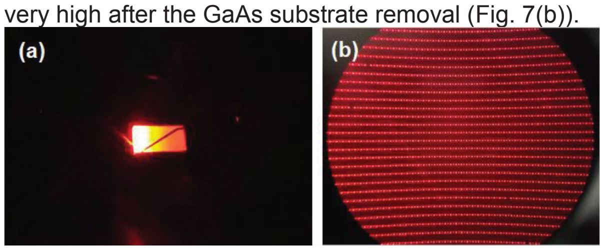


Fig. 7 (a) All pixels were turned on AlGaInP red micro-LED array. (b) Pixel view under microscope.

After the hybrid integration of the monolithic blue GaN-on-Si micro-LED micro-display and the monolithic fabricated AlGaInP red micro-LED array, an active-matrix blue/red dual-color micro-LED micro-display was achieved. Fig. 8(a) demonstrates that all of the red and blue pixels are turned on in the dual-color micro-display. A barely satisfactory yield can be achieved in this preliminary demonstration. The zoomed-in photo shows the pure blue and red light emission coming from the GaN blue micro-LEDs and AlGaInP red micro-LEDs (Fig.8 (b)). The blue light is transmitted through the window regions of red micro-LED array, as discussed in the previous section. High brightness can be obtained by directly increasing the driving current of pixel drivers.

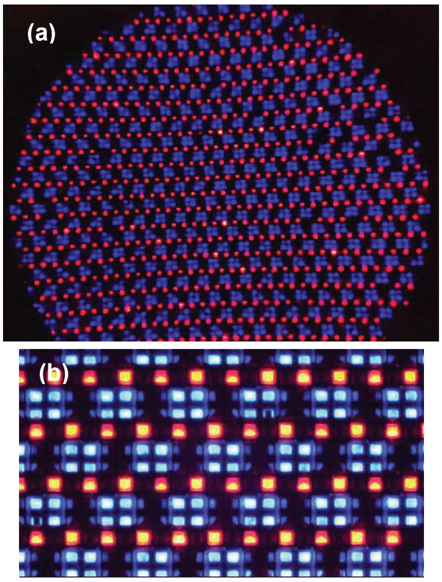


Fig. 8 (a) Overview and (b) pixel view of the hybrid-integrated blue/red dual-color micro-LED micro-display.

4 Discussion and Conclusions

Here we demonstrate a prototype of hybrid-integrated monolithic active-matrix blue/red dual-color micro-LED micro-display by twice of flip-chip bonding. The monolithic fabricated GaN-on-Si blue micro-LED array was firstly bonded onto the Si CMOS driver and the monolithic fabricated AlGaInP red micro-LED array was then flip-chip bonded to the GaN thin-film micro-LED micro-display via the window regions formed by AlGaN buffer etchback. Without using QD-based color conversion materials, higher brightness and much purer color can be expected. Without pixel level transferring, high pixel density can be achieved through the monolithic micro-LED array fabrication method. Therefore, this hybrid dual-color micro-LED micro-display possesses both of the advantages of mass transfer and monolithic fabrication methods so that pure color, high brightness and high pixel density can be achieved simultaneously. For the small-size micro-display applications, we expect this hybrid integration will be a promising method in the future. Moreover, the realization of full-color micro-LED micro-displays through this integration method will be further explored.

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