Monolithic Thin Film Red LED Active-Matrix Micro-Display by Flip-Chip Technology

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Abstract—A monolithic thin film red light emitting diode (LED) active-matrix (AM) micro-display driven by a complementary metal-oxide semiconductor (CMOS) driver is demonstrated. The resolution of the micro-display is 64 × 36, with a 40 μm × 40 μm pixel pitch. Starting from AlGaInP epi-layers grown on GaAs substrates, the monolithic red LED array was fabricated and then integrated with the AM driver using Au/In flip-chip bonding technology. After removal of the GaAs substrate, a crack-free thin film micro-display was realized with a high pixel yield. The thin film red LED AM micro-display delivers a luminance of 2.35 × 10^4 cd/m^2 at full-load conditions and can render images with 4-bit grayscale. This work not only provides a manufacturing-friendly approach for monolithic thin film red LED micro-displays, but also brings the possibility of hybrid integration with blue/green LEDs to achieve full-color LED micro-displays.

Index Terms—Active-matrix, AlGaInP, light emitting diode, micro-display, flip-chip device, thin film device.

I. INTRODUCTION

VIRTUAL reality (VR) and augmented reality (AR) electronics provide attractive immersion and interactive experiences to users in professional training, surgery, entertainment and other interactive scenarios. Micro-displays are one of the core components in VR/AR devices. Unlike displays for televisions and desktops, micro-displays feature very small dimensions (typically < 1 inch), fine pixel pitch and high brightness to meet the requirements of VR/AR devices [1]. Liquid crystal micro-displays such as liquid crystal on silicon (LCoS), are based on the light modulation properties of liquid crystals. They require a power-hungry backlight unit for the severe light loss and the contrast ratio is limited to a low level [2]. While self-emissive devices such as organic light emitting diode (OLED) micro-displays are a more appealing choice than liquid crystal, OLED technology has challenges in terms of efficiency and reliability, especially for blue OLED materials [3]. Alternatively, self-emissive inorganic light emitting diodes (LEDs) offer higher brightness, a shorter response time and a longer working lifetime, and thus have been considered to be a promising option for micro-displays [4].

Inorganic LED micro-displays can be monolithically fabricated on LED epi-wafer grown by metal organic chemical vapor deposition (MOCVD). Because the monolithic approach does not involve any pixel-transfer process, small-size and high-resolution micro-displays can be realized [1], [4], [5] with conventional complementary metal-oxide semiconductor (CMOS) technology, leading to a potentially high pixel yield and lower cost compared with pixel-transfer technology [6]. Research into monolithic LED micro-displays started in 2001 [7], and progressed in the following decades in aspects such as high resolution realization [8], flip-chip integration [9], [10] and active-matrix (AM) driving [11], [12]. Most of these works focused on blue or green InGaN LEDs. Due to the inefficient red emission of InGaN LEDs, red micro-LED displays are fabricated using AlGaInP epi-layers grown on GaAs substrates. However, the GaAs substrates are opaque and electrically conducting, making it impossible to fabricate addressable LED pixel arrays on the original growth substrate. Moreover, the red AlGaInP LED epi-layers are usually thick (8-15 μm), which is also challenging for the fabrication of micro-LEDs. Consequently, a feasible technology to fabricate monolithic red LED micro-displays is yet to be established, limiting the applications of LED micro-displays in full-color VR/AR devices.

Multiple works have attempted to overcome the technical issues of monolithic red LED micro-displays. A straightforward solution is to transfer AlGaInP epi-layers onto transparent and insulating sapphire substrates prior to the fabrication of LEDs [13]. Both passive-matrix (PM) [14] and AM [15] red LED micro-displays have been demonstrated using AlGaInP on sapphire epi-wafers. However, a desirable pixel pitch in VR/AR devices should be less than 50 μm, smaller than what was reported in the past. Furthermore, this transfer technology produces an additional epi-layer transfer cost, while light crosstalk among pixels is induced through the transparent substrate [16]. Instead of using a sapphire substrate, thin film red LED micro-displays have been hybridized with a CMOS driver by eutectic bonding of AlGaInP epi-layers [17]. Although this approach can realize high pixel density with less light crosstalk, it is critical to prevent bonding failure induced by strain and high temperature processes during the complicated fabrication after bonding.

In this work, monolithic red LED micro-displays are firstly fabricated on AlGaInP/GaAs epi-wafers, and then integrated with AM CMOS drivers by flip-chip bonding technology. After bonding, removal process of the GaAs substrate is implemented, preventing any possible pixel damage in the complicated post-bonding processes. The thin film AM micro-displays also exhibit limited light crosstalk and high...
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Before the flip-chip bonding, a 10-second reflow process was performed for the evaporated indium patterns to form soldering bumps at 180 °C, with the aid of water-soluble soldering flux in a formic acid atmosphere. Because indium does not adhere to the EOC polymer layer, it spontaneously flowed into the contact holes driven by surface tension and was reshaped into indium bumps. The heights of the indium bumps were 8-10 µm, sufficient to offset the 5 µm height difference between the p- and n-electrodes. Thicker bonding pads can be deposited on the n-electrodes of the CMOS driver, thus further offsetting the height difference in the future work. Fig. 4 (a) provides an inspection photomicrograph of uniformly distributed indium solder bumps on the p- and n-electrodes. After the reflow process, the red LED array chip was flip-chip bonded to the AM driver (Fig. 4 (b)) under a bonding force of 10 N at 180 °C for 1 minute in a formic acid atmosphere.

To obtain a thin film LED micro-display, the 350 µm-thick opaque GaAs substrate must be removed after the flip-chip bonding. An ammonia/H₂O₂ mixture is widely used to etch thick GaAs [18], [19]. It is selective to GaInP, so the etching process terminates at the GaAs/GaInP interface. However, this etchant is highly reactive to most metals. To protect the underlying driver and LED pixels, the periphery of the LED chip and the AM driver was covered by photoresist. The photoresist was hard-baked at 120 °C for at least 30 minutes to enhance the adhesion and strength. The integrated micro-display with photoresist protection was etched in the ammonia/H₂O₂ for approximately 1 hour until a smooth, mirror-like GaInP surface was exposed. Fig. 5(a) shows the thin film micro-display after removal of the GaAs substrate. (b) The driving PCB for the micro-display demo.

The display controller is an Arduino-based board and all the control signals are sent to the driving PCB via a flexible cable. The monolithic thin film red LED AM micro-display can be demonstrated on this driving platform.

![Image](Image69x533 to 279x614)

**Fig. 4.** (a) Indium solder bumps formed by the reflow process. (b) The red LED array integrated with the CMOS AM driver by flip-chip bonding, before removal of the GaAs substrate.

**Fig. 5.** (a) The monolithic thin film red LED AM micro-display after removal of the GaAs substrate. (b) The driving PCB for the micro-display demo.

![Image](Image78x651 to 270x734)

**Fig. 6.** (a) Typical I-V characteristics of red LED pixels (with GaAs substrates) after p- and n-electrode deposition. The inset is the emission photomicrograph of a single pixel and the EL spectrum. (b) The I-V characteristics of red LED pixels with/without GaAs substrates and the output characteristics of the pixel driver.

**IV. RESULTS AND DISCUSSION**

Fig. 6(a) plots representative I-V characteristics of a single red LED pixel after deposition of the n- and p-electrodes. The forward voltage is 1.82 V at 90 µA (∼10 A/cm²) and 1.92 V at 450 µA (∼50 A/cm²), showing reasonable contact resistances and turn-on performance of the p- and n-electrodes. The reverse leakage current is 1.77 nA at -5 V. The inset shows the electroluminescence (EL) spectrum and the emission image of a red LED pixel. The peak emission is 627 nm with a full width at half maximum (FWHM) of 22 nm.

To estimate the I-V characteristics of thin film LED pixels on the CMOS driver, the LED array was flip-chip bonded on a test carrier that had a similar layout to the CMOS driver. The I-V characteristics were measured after removal of the GaAs substrate. Fig. 6(b) plots the I-V characteristics of the LED pixels with and without the GaAs substrate. After removal of the GaAs substrate, the forward voltage of the thin film LED pixels is 2.23 V at 90 µA (∼10 A/cm²), which represents an increase of 0.41 V. The curve becomes more linear rather than exponential, implying that the series resistance of the LEDs increases somewhat. This indicates that the driving current of the original LED pixels mainly passes through the thick, highly conductive n-GaAs substrate. In the thin film LEDs without GaAs, the driving current must move laterally through the 3 µm-thick n-AlGaNp layer, leading to a higher series resistance. Despite this, the operating voltage of the LED pixels still lies within an acceptable range.

The output current of the AM pixel driver when driving the thin film red LED pixels was estimated. The schematic design of the AM pixel driver is illustrated in our previous publication [22]. The supply voltage of the AM pixel driver was measured to be 3.32 V. The pixel driver and the LED pixels are serially connected, and thus the increase in the operating voltage of the LED leads to a decrease in the driving current, as shown in the output characteristics of the pixel driver plotted in Fig. 6(b). The operation point of the thin film LED pixels is around 2.28 V and 98 µA (∼11 A/cm²). The total power consumption of the thin film red LED array is 0.5 W under full-load conditions, and the luminance is about 2.35 × 10⁴ cd/m². The micro-display has the potential...
to achieve a luminance of over $10^5 \text{ cd/m}^2$ at higher driving current density.

Images rendered by the monolithic thin film red LED AM micro-display are demonstrated in Fig. 7. All pixels were connected to the driver and powered up. The all-lit-up image (Fig. 7 (a)) indicates a uniform emission over the whole display area. Some pixels, especially those at the edge region, are darker than the others due to poor contact of solder bumps. It will be improved by applying a more uniform bonding force when performing flip-chip bonding. The stripe patterns (Fig. 7 (b)) clearly show the capability of 4-bit grayscale control. The patterns/texts on a black background (Fig. 7 (c)) demonstrate that there is no significant light crosstalk problem compared with flip-chip LED micro-displays with sapphire substrates [10]. The portrait image (Fig. 7 (d)) proves that the micro-display can provide good visual effects and present sufficient details.

V. CONCLUSION

A monolithic thin film red LED AM micro-display is demonstrated in this work. The resolution of the micro-display is 64 × 36 pixels with a 40 µm pixel pitch. The red LED array was monolithically fabricated starting from commercial AlGaNp epi-layers grown on GaAs substrates. The red LEDs have a lateral electrode structure, and they were integrated with an AM micro-display driver by Au/In flip-chip bonding. The opaque GaAs substrate was removed by a wet etching process, leaving the backside-emitting thin film red LED pixels on the driver. The thin film red LEDs are crack-free and the bonding yield is high. The display performance of the micro-display was evaluated on our driving platform. It presents a luminance of 2.35 × $10^4 \text{ cd/m}^2$ under full-load conditions, with a 0.5 W power consumption of the LED array. Images shown with 4-bit grayscale prove the display capability of this red LED micro-display and the feasibility of practical applications. This work provides a simple, cost-effective approach for monolithic thin film red LED micro-displays, suggesting tremendous potential for integrating red AlGaNp LEDs with blue/green InGaN LEDs to realize full-color micro-displays.

REFERENCES


