360 PPI Flip-Chip Mounted Active Matrix Addressable Light Emitting Diode on Silicon (LEDoS) Micro-Displays

Zhao Jun Liu, Wing Cheung Chong, Ka Ming Wong, and Kei May Lau, *Fellow, IEEE*

***Abstract*—In this paper, we describe the design and fabrication of 360 PPI flip-chip mounted active matrix (AM) addressable light emitting diode on silicon (LEDoS) micro-displays. The LEDoS micro-displays are self-emitting devices which have higher light efficiency than liquid crystal based displays (LCDs) and longer lifetime than organic light emitting diodes (OLEDs) based displays. The LEDoS micro-displays were realized by integrating monolithic LED micro-arrays and silicon-based integrated circuit using a flip-chip bonding technique. The active matrix driving scheme was designed on the silicon to provide sufficient driving current and individual controllability of each LED pixel. Red, green, blue and Ultraviolet (UV) LEDoS micro-displays with a pixel size of 50 μm and pixel pitch of 70 μm were demonstrated. With a peripheral driving board, the LEDoS micro-display panels were programmed to show representative images and animations.**

***Index Terms*—Active circuits, displays, flip chip, light emitting diodes (LED).**

I. Introduction

In the past several years, LEDs have gradually substituted cold cathode fluorescent lamps (CCFLs) as the backlight of liquid crystal displays (LCDs) due to better luminous efficiency, long lifetime and wide color gamut [1]–[4]. Although many technologies have been developed to reduce the power consumption, extremely low light utilization efficiency (LUE) of the backlight system in the LCD panels renders further power reduction difficult [5]–[7]. Sequential color display can improve the LUE by about 2.7 times by removing the red, green and blue color filters. The system LUE however is still as low as 7.56% by calculation [8]. LEDs, self-emitting devices without the need of backlight units, are suitable for many applications such as illumination and novel displays. LED micro-displays have the potential to enhance and improve the present capabilities of small LCDs and OLED displays with its excellent performance in many different aspects, particularly high LUE, simplicity of optical modules without backlight unit, long lifetime and excellent visibility under bright daylight. Passive matrix-addressable LED micro-displays on sapphire substrates have been reported [9]–[12]. The dimensions and pixel brightness in passive addressable LED micro-displays are limited by the loading effect because the LED pixels in the same row or column share the fixed driving current of the periphery driving supplies. The power efficiency of passive matrix LED micro-displays was also low because of parasitic resistance and capacitance with a large amount of connecting wires. LED arrays addressed by a single transistor with epitaxial stack method were also deployed [13], [14]. For single transistor addressable LED arrays, the pixel brightness is limited by the current driving capability of the signal source. In addition, the data signal cannot be held without storage capacitors after the scanning period, resulting in a low display brightness and quality. Monochromatic active matrix addressable LED micro-displays with individual CMOS driving circuits that are capable of storing data and driving each individual LED pixel were reported recently [15]–[17].

In this paper, we describe the design and fabrication of 360 PPI LEDoS micro-displays with red, green blue and UV colors by integrating monolithic LED micro-arrays and active matrix substrates using Flip-Chip technology. A CMOS active matrix driving scheme was designed to provide sufficient drive capability and individual controllability of each LED pixel. The LEDoS micro-displays had 60×60 pixels on a single chip. The circular shape pixels had a diameter of 50 μm and a resolution of 360 PPI. The emission wavelengths of the LEDoS micro-displays were 630 nm, 535 nm, 445 nm, and 380 nm, respectively. The red, green and blue LEDoS micro-displays can be used to form a novel full-color direct-view display. The UV LEDoS micro-display could be used for modulated visible light communication systems or for data-modulated photo-pumped organic semiconductor devices [18].

II. Experiment

A LEDoS micro-display includes a monolithic micro-LED array and a silicon-based AM substrate. The UV, blue and green micro-LED arrays were fabricated from GaN-based multi quantum well (MQW) LED structure grown on sapphire substrate, as shown in Fig. 1(a). For red micro-LED array, the LED structure was grown on GaAs substrate and then transferred to sapphire substrate, as shown in Fig. 1(b).

The micro-LED arrays contain a 60×60 array of individually addressable micro-disk pixels 50 μm in diameter with a center to center pitch of 70 μm. The micro-LED pixels share a common cathode (n-electrode) with an independently controllable anode

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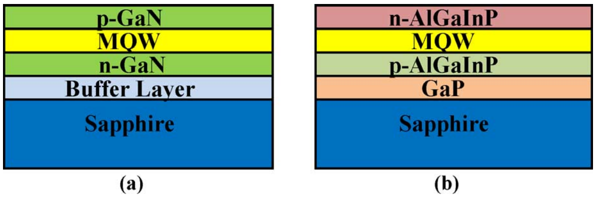


Fig. 1. (a) Epi-structure of UV, blue and green micro-LED arrays. (b) Epi-structure of red micro-LED arrays.

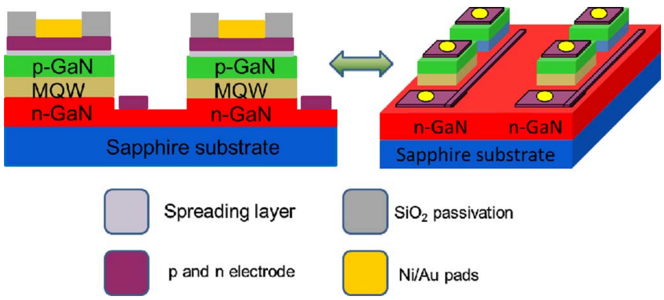


Fig. 2. Cross-sectional and 3D view of the micro-LED pixels.

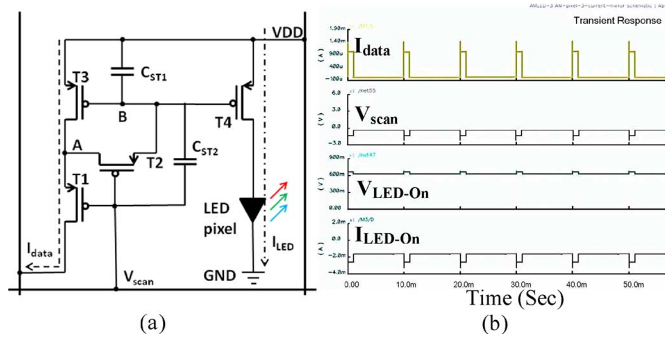


Fig. 3. (a) Schematic of the driving circuit of the active matrix substrate. The current-ratio circuit consists of four PMOS transistors and corresponds to one micro-LED pixel. (b) Spectra simulation results of the current ratio circuit.

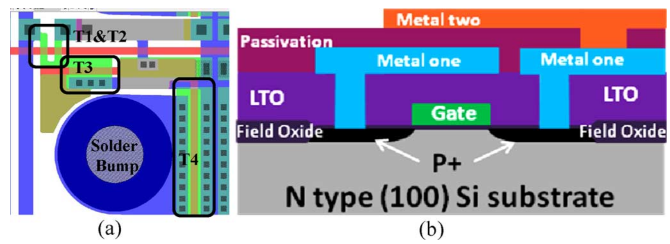


Fig. 4. (a) Layout and (b) cross-sectional view of the driving circuit.

(p-electrode). The mesa structure of the pixels was defined using photolithography and inductively coupled plasma (ICP) etching with SiO_2 as a hard mask. 10 nm of Ni/Au was evaporated onto the p-GaN area to serve as the current spreading layer (CSL). Then, a 200 nm Ti/Al/Ti/Au stack layer was evaporated onto the p-GaN and n-GaN as electrode. This Ti/Al/Ti/Au stack layer served as reflective mirror at the p-GaN light emitting region. A SiO_2 isolation layer was deposited by plasma enhanced chemical vapor deposition (PECVD) and patterned by reactive ion etching (RIE) and 350 nm Ni/Au was deposited on pad area of p-electrode and n-electrode for flip-chip bonding. Finally, the 420 μm-thick sapphire substrate was mechanically polished to 100 μm thick and the thinned wafers were diced into individual device chips of an area of approximately 4.5 mm $\times$ 4.5 mm. A cross-sectional diagram and a 3D view of the micro-LED array are shown in Fig. 2.

The custom-designed active matrix substrate, implemented with a 2 μm feature size CMOS technology from the Nanoelectronics Fabrication Facility (NFF) in the Hong Kong University of Science and Technology, consists of 3600 driving circuits in a 60$\times$60 array. Each driving circuit maps to one micro-LED pixel with a pitch of 70 μm. Fig. 3(a) illustrates the circuit diagram and Fig. 3(b) shows the Cadence simulation results of the driving circuit. Since the micro-LED pixels were common cathode connected because of the growth structure, p-type metal–oxide–semiconductor (PMOS) transistors were chosen as drivers, and the anode of the micro-LED pixel was connected to the drain terminal of the transistor. The advantage of this configuration is that the uniformity and degradation of the micro-LED pixels would not affect the output current of the driving transistor [19]. Each driving circuit consists of two switching transistors (T1 and T2), one mirror transistor (T3) and two storage capacitors $(C_{\rm ST1}, C_{\rm ST2})$. The two capacitors are connected between a scan line and VDD with a cascade structure. The signals of $V_{\rm scan}$, $I_{\rm data}$ and VDD are applied by the external drivers, respectively. The anode and cathode of the micro-LED pixel were connected to the drain terminal of T4 and the common ground, respectively. During the ON-state, $V_{\rm scan}$ turns on T1 and T2, and $I_{\rm data}$ passes through T1 and T3 as the dashed line shown in Fig. 3(a) and sets up the voltage at T2 source terminal (Node A). At the same time, the voltage at T3 gate terminal (Node B) is set by $I_{\rm data}$ passing through T3. Since $I_{\rm data}$ is a current source, the gate voltage of T3 is automatically set low enough to allow the fixed $I_{\rm data}$ flowing through T1 and T3. The current passing through the LED is controlled by the geometry ratio of the transistors T3 and T4 with the relationship of

$$I_{\rm LED-On}/I_{\rm data} = \frac{W_{T4}/L_{T4}}{W_{T3}/L_{T3}}. \tag{1}$$

The fabrication process of the silicon driving circuit started with (100) single crystal silicon wafers. Field oxide was grown to define active islands followed by gate oxidation. Then a layer of poly-Si was deposited and patterned as gate electrode. After source/drain self-aligned ion-implantation, contact holes were opened through a layer of low temperature oxide (LTO). Aluminum–silicon alloy was deposited by sputtering and patterned as the first metal interconnects. 700 nm SiO_2 was deposited by PECVD and via holes were opened through it. Fig. 4(a) shows the layout and (b) the cross-sectional view of the driving circuit on the silicon-based active matrix substrate.

Flip-Chip bonding process was used to electrically and physically connect the micro-LED array and the AM substrate. With this configuration, the LEDoS micro-display was top-emitting and the aspect ratio could be as high as 40%. The process is described as follows. A 10 μm-thick PR4620 was coated and patterned onto the AM substrate. Then a 100 nm Ni/Au layer was sputtered as an adhesive layer and diffusion barrier of indium.

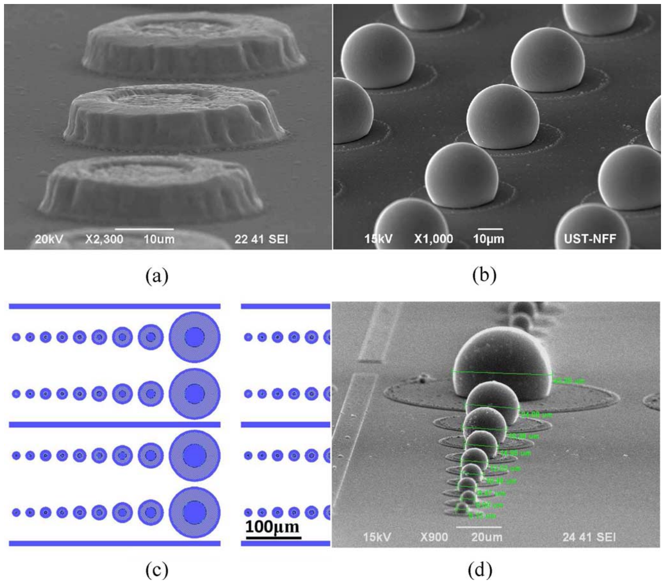


Fig. 5. (a) Illustration of a scanning electron microscopy (SEM) image of the disk-like indium pattern. (b) An SEM image of the solder bumps after the reflow process. (c) Testing structure of solder bumps. (d) Solder bumps with different diameters. The smallest one has diameter of 5 μm.

A 6 μm-thick Indium was then thermally evaporated and patterned by a lift-off process. After annealing in a reflow furnace, the disk-like indium [see Fig. 5(a)] transformed a ball-shape solder bump [see Fig. 5(b)]. After indium reflow, the micro-LED array was flip-chip bonded onto the AM substrate by a SET FC150 flip-chip bonding machine with a bonding temperature of 150 °C and a pressure of 0.7 g per solder bump. To check the scaling-down capability of the flip-chip process, a set of testing structures of solder bumps were designed with various diameters as shown in Fig. 5(c). A SEM image of the indium testing structures after the reflow process is shown in Fig. 5(d). The smallest solder bump has a diameter of 5 μm, which provides possibility of an ultra-high resolution LEDoS micro-display in the near future.

III. Results and Discussion

Fig. 6 shows the current–voltage (*I–V*) characteristics and the inset is the optical output power versus driving current (*L–I*) characteristic from an individual UV micro-LED pixel, driven by the pixel circuit under direct current (dc) bias conditions at room temperature. The *I–V* characteristics of the micro-LEDs were measured by a HP 4156A semiconductor parameter analyzer. One micro-LED in every seven pixels in the same row was measured. The VF variation was 0.4 V at an injection current of 20 mA. The equivalent VF variation at a current density of a 300 μm×300 μm area which is typically used for standard LEDs is smaller than 0.05 V, exhibiting excellent electrical uniformity. The inset illustrates that the UV LED pixel had 154 μW light output power at an injection current of 10 mA with a light output power density of 7.84 W/cm ^{2}.

Photoluminescence (PL) was measured on the LEDoS micro-displays by a 33 mW He–Cd laser with a wavelength of 325 nm. From the PL results shown in Fig. 7, it was found that the LEDoS micro-displays had a wavelength of 630 nm, 535 nm, 445 nm, and 380 nm, respectively. The red, green and blue LEDoS micro-displays can be used as single monochromatic displays or a full-color projection display with 3-in-1 combination by a prism. The projection experiment and results will be discussed in other publication. Red, green and color phosphors were deposited on the UV LEDoS micro-displays to demonstrate a full-color display. The phosphors excitation and emission results were discussed in another publication [20].

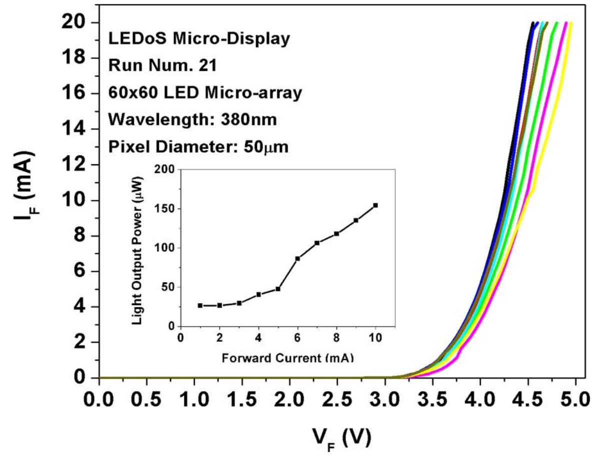


Fig. 6. I-V characteristic of UV micro-LED pixels in a same row. Inset shows the L-I characteristic of a representative UV micro-LED pixel.

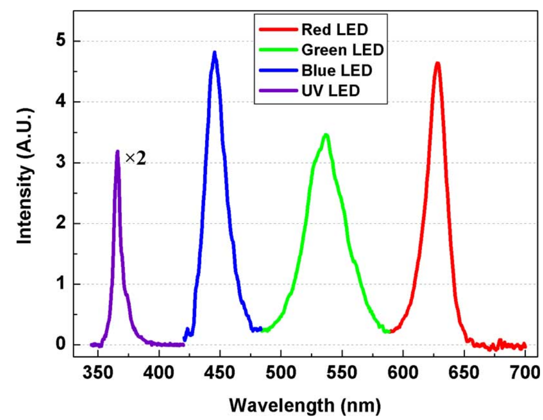
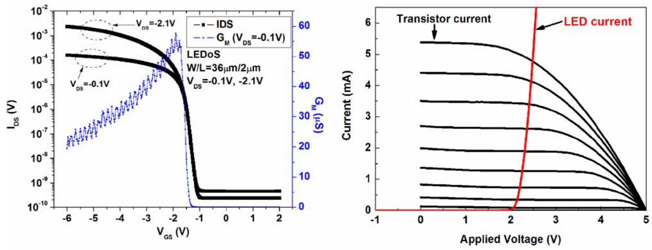


Fig. 7. Light output spectrum of the UV, Blue, Green, and Red micro-LED pixels.

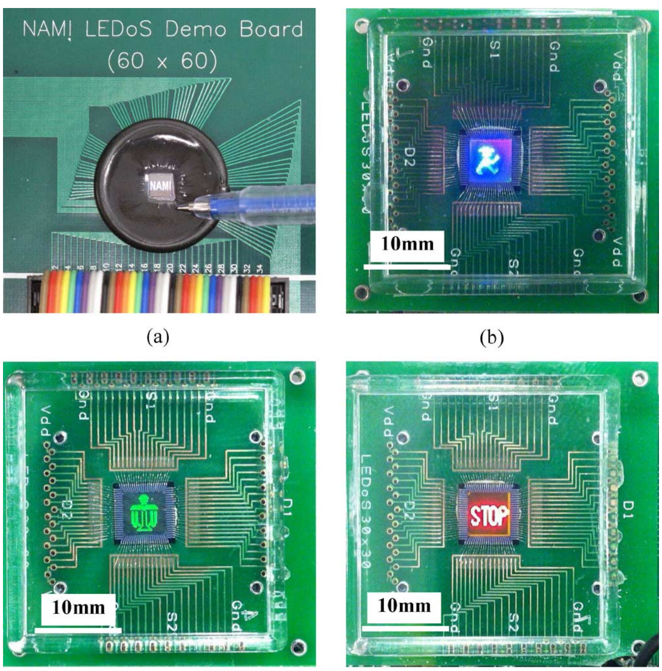
Fig. 8(a) illustrates the transfer characteristics ($I_{\rm DS}$-$V_{\rm GS}$) curve and Fig. 8(b) shows the output characteristics ($I_{\rm DS}$-$V_{\rm DS}$) curve of the PMOS driving transistor T4. The single crystal silicon PMOS allows a high output current of 6 mA for each micro-LED pixel and an equivalent power density of 122 A/cm^2. The on/off current ratio was measured of $\sim 10^7$. The operation points of the driving transistor and the micro-LED pixel are shown in Fig. 8(b). It is noted that the active matrix substrate has sufficient capability of driving the micro-LED array.

After wire-bonding and encapsulation of the LEDoS chips, periphery driving boards were designed to demonstrate the LEDoS micro-displays. With peripheral driving boards, the LEDoS micro-display panel was programmed to display representative images such as the HKUST logo, and traffic



(a) (b)

Fig. 8. (a) $I_{\rm DS}$-$V_{\rm GS}$ curve and (b) $I_{\rm DS}$-$V_{\rm DS}$ curve of the PMOS driving transistor of the current-ratio pixel circuit. Operation points of the driving transistor (Black line) and the micro-LED pixel (Red line) are also showed in (b).



(a) (b) (c) (d)

Fig. 9. Representative display results of LEDoS micro-displays with emission color of: (a) UV (b) Blue (c) Green and (d) Red.

instructions as shown in Fig. 9. The LEDoS has potential application such as micro-displays, portable projectors, bio-sensor arrays, backlight units for LCDs and programmable lighting sources.

IV. Conclusion

In this work, 360 PPI active matrix addressed LEDoS micro-displays were demonstrated. The LEDoS micro-displays exhibited red, green, blue and UV color with emission wavelength of 630 nm, 535 nm, 445 nm, and 380 nm, respectively. Unlike LCDs, the LEDoS micro-displays are self-emitting and do not need a backlight unit. The light utilization efficiency is as high as 100% due to the optical simplicity. The micro-LED array was flip-chip bonded onto the silicon-based AM substrate with an aspect ratio of 40%. Full-color displays using three currently available monochromatic LEDoS micro-displays can be realized using projection optics. The present study clearly demonstrated that LEDoS displays are a favorable, complementary technology to the mature LCDs, OLED displays, liquid crystal on silicon (LCOS) and digital light processors (DLPs).

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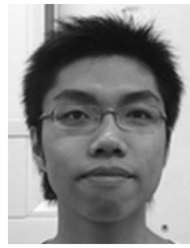

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