P-34: Active Matrix Programmable Monolithic Light Emitting Diodes on Silicon (LEDoS) Displays

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ABSTRACT

In this paper, the first full-color active matrix programmable monolithic Light Emitting Diodes on Silicon (LEDoS) displays are fabricated using flip-chip technology. The forward voltage uniformity of the LED pixels was greatly improved by a double-side ground structure. A basic LED micro-array module was fabricated and the AM substrate has scaling-up ability. By integrating a certain number of LED micro-array modules onto a large-scale AM substrate, a large-scale display is obtained. By this scaling-up method, the utilization rate of the LED wafers is increased significantly. The yield of the LED pixels is improved simultaneously. Red, green and blue phosphors were excited by UV light to realize a full-color display.

1. Introduction

Flat panel display (FDP) becomes the major type of display technology nowadays, among which the liquid crystal display (LCD) is the most competitive. Backlight units (BLU) are used as light sources of LCD panels, which determine the key performances of LCD such as the brightness, contrast, colors saturation, power consumption and environmental friendliness. Comparing with conventional cold cathode fluorescent lamp (CCFL), light emitting diode (LED) BLU is essential for a high quality LCD because of its superior characteristics such as higher brightness, longer lifetime and lower power consumption [1]. However, most portion of the light is lost on the LCD system.

Fig.1 shows the light loss on the conventional LCD system [2]. After passing through the polarizers, TFT backplane panel, LC layers and color filters, only 2.8% of the light can be taken into efficient. In recent years, field sequential color (FSC) technology is developed to improve the optical efficiency and color saturation. This method can produce a bright display since no color filters are used. The number of the pixels of a FSC LCD is only one third of that of a color filter display. So a higher aperture ratio (AR) is achieved. However, the FSC LCD can only improve the light output from 2.8% to 8.76%. The most significant concern for FSC displays is the presence of color breakup (CBU) artifacts [3]. Moreover, the refresh frequency is three times higher than the color filter LCD which brings big challenges to the LC materials and thin film transistor (TFT) driving circuits.

LED has spontaneous properties for FDP applications such as self-emission, long lifetime, low operation voltage, various available colors and good reliability in many extreme environments with low/high temperature, low/high air pressure, humidity even outer space radiation [4]. Passive matrix programmable LED arrays are widely used in communication systems and outdoor/indoor LED large-screens. The pixel pitches of these applications are ranges from several millimeters to several centimeters. A long view distance is always needed to observe the displayed images. In addition, the passive matrix driving scheme has many disadvantages such as cross-talk, loading effect, power consumption on large number of connection wire. The size and bulk of the passive matrix LED arrays make them impossible to meet the applications of portable displays, indoor LED TVs and bio-medical detection sensors. LED micro-arrays have high resolution, high power density and are one of the best candidates of portable electronic applications [5].

In this paper, the first full-color active matrix programmable monolithic Light Emitting Diodes on Silicon (LEDoS) displays are fabricated using flip-chip technology. The forward voltage uniformity of the LED pixels was greatly improved by a double-side ground structure. A basic LED micro-array module was fabricated with resolution of 8×8 and pixel pitch of 550μm. By integrating a certain number of LED micro-array modules onto a full-custom designed large-scale active matrix (AM) substrate, a large-scale display is obtained. Red, green and blue phosphors were excited by UV light to realize a full-color display.

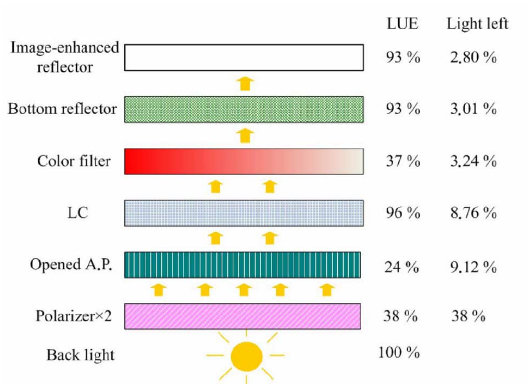


Fig.1 LCD light output based on light losses per layer [2]

2. Experiment

The fabrication included three main parts: LED micro-array process, active matrix substrate process and integration process. The detailed process steps of LED micro-array and active matrix substrate were discussed in other paper [6]. Here, the integration process and phosphors deposition process will be discussed.

The integration process was as follows: after fabrication of the active matrix substrate, PR4903 was coated and patterned with a thickness of 30μm. Then

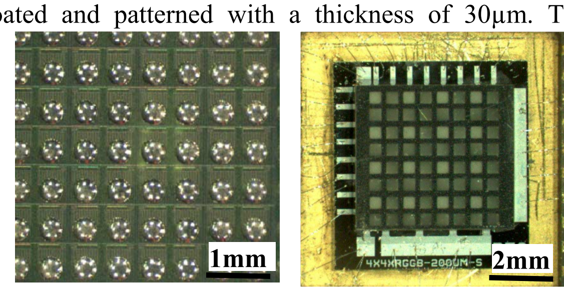


Fig.2 (a) solder bumps seating on top of active matrix substrate and (b) microscope image of LEDoS module after RGB phosphors deposition

TiW/Cu layer was sputtered. After that Cu and solder layers were deposited by electrical plating. Lift-off process was used to pattern the Cu and solder layers. After that the sample was reflowed to form solder bumps. Fig. 2(a) shows the microscope image of the active matrix substrate after solder bumps forming. After solder bumps forming, certain numbers of LED micro-array modules were flip-chip bonded onto the active matrix substrate. Silicon moulds for RGB phosphors deposition were fabricated by etching through a single crystal silicon wafer. Then phosphors were deposited in the etching holes by dispenser. Fig. 3 shows the microscope images of the LEDoS display panels after flip-chip bonding.

3. Results and discussion

3.1 Electrical uniformity of the LED pixels

Fig.3(a) shows the layout structure of the 8×8 LEDoS module. The pixel size is 500μm with a pitch of 550μm. n-electrodes are designed at both the left and right sides and each pixel was surrounded by the extension of the n-electrodes. The n-electrodes at both sides connect to the ground terminal on the active matrix substrate. This structure is named double-side ground structure. Fig.3(b) shows the current flowing diagram. With double-side ground structure, uniform current distribution is realized and the forward voltage (V_F) variation is eliminated.

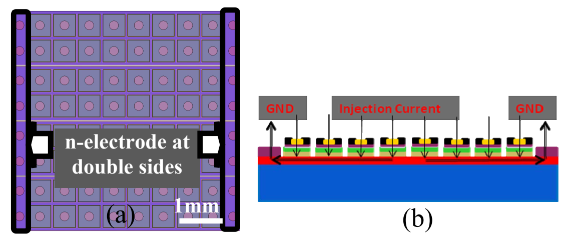


Fig. 3 (a) Layout of the 8×8 LED micro-array module and (b) current flow of 8 LED pixels in a row

For comparison, three types of n-electrode structures were designed and fabricated together with double side ground structure as shown in Fig.4. Design (a) had single side n-electrode and no optimization. Design (b) had single side n-electrode and 40μm-wide n-metal line. Design (c) had single side n-electrode and the LED pixel was surrounded by n-electrode metal. Design (d) had both double-side ground and n-metal surrounding structures.

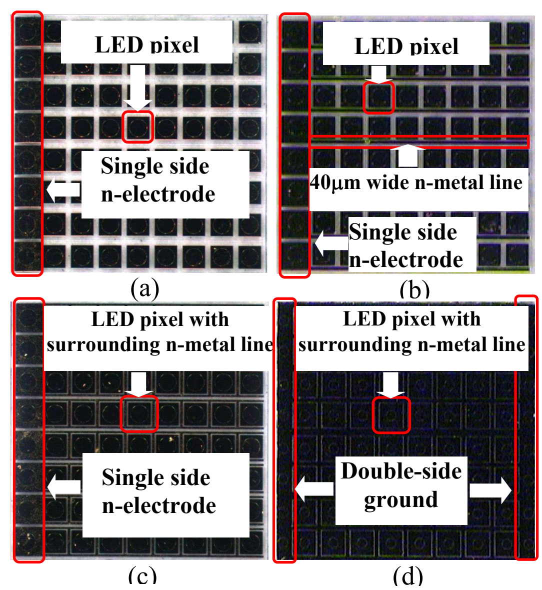


Fig.4 (a) without any optimization; (b) with 40μm-wide n-metal line; (c) with n-metal surrounding; (d) with n-metal surrounding and double-side cathodes

Current-voltage (I-V) characteristics of LED pixels were measured by an HP 4155A semiconductor parameter analyzer. Fig.5(a) shows the I-V characteristics of 8 LED pixels in the same row of double-side ground structure. The V_F of the LEDs have excellent uniformity with a variation of 0.02V. From comparison in Fig.5(b), the V_F variation of design (a) (b) (c) and (d) are 81.9%, 16.2% 4.7% and 0.6%, respectively. A significant improvement on electrical uniformity is achieved by the double-side ground structure.

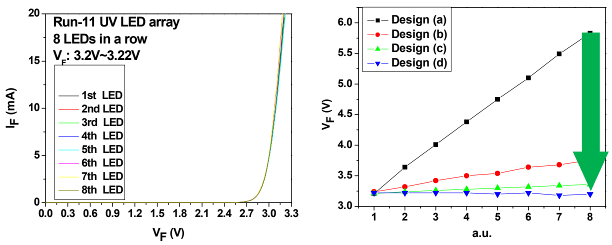


Fig. 5 (a) I-V characteristics of 8 LEDs in the same row of double-side ground structure; (b) V_F variation of LED pixels with four designs

3.2 Emission wavelength

Blue light and ultraviolent (UV) LEDoS displays were fabricated. Fig.6 shows the display results of the blue light LEDoS module. The LED pixels had high brightness, good luminance uniformity and individual controllability by the active matrix substrate.

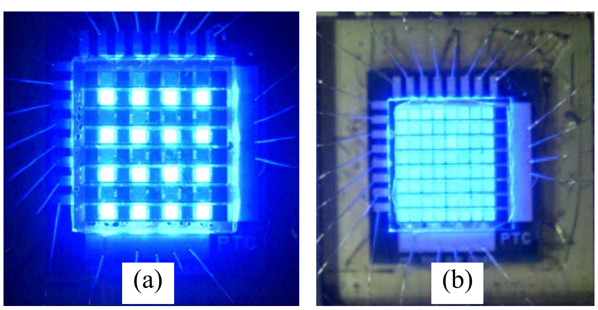


Fig. 6 The blue light LEDoS module was (a) individually lit up and (b) fully lit up

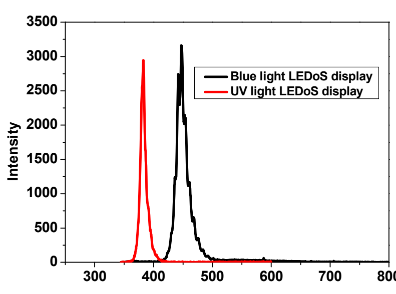
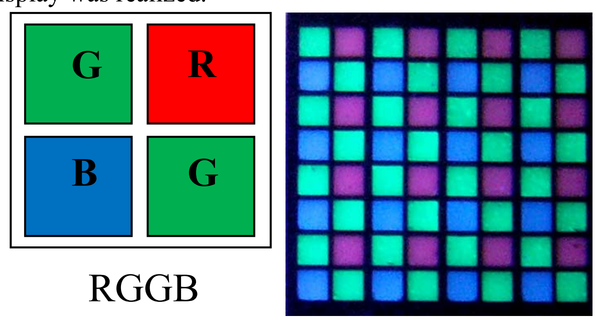


Fig. 7 Wavelength of blue and UV LEDoS displays

Photoluminescence (PL) was measured on the LED by a 33mW laser beam with a wavelength of 325nm. From the PL results shown in Fig.7, we can find that the LED pixels had a wavelength of 460nm (blue) and 380nm (ultraviolent).

3.3 Excitation & Emission results of RGB phosphors

To realize a full-color display, one colorful pixel included four sub-pixels in combination of two red, one green and one blue (RRGB) as shown in Fig.8(a). Silicon moulds were fabricated by etching through a single crystal silicon wafer using deep reactive-ion etching (DRIE). Then phosphors with individual emission wavelength were dropped to the corresponding etching holes on the moulds. After solidification, excitation & emission experiments were performed by UV LEDs with emission wavelength mentioned in Fig.7. From Fig.8(b), the phosphors emitted individual colors and a full-color display was realized.



(a) (b)

Fig. 8 (a) One colorful pixel includes four sub-pixels in combination of RGGB and (b) a full-color display by excitation of RGB phosphors by UV LEDs

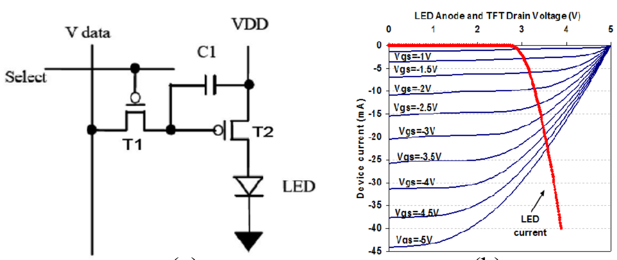
3.4 Driving capability of the LEDoS displays

The pixel circuit of the active matrix substrate includes two pMOS transistors; one capacitor and the LED pixel, as shown in Fig.9 (a). Transistor T1 serves as selecting transistor and transistor T2 serves as driving transistor. When selecting signal is applied, T1 will switch on and data signal passes through to the gate of T2 and charges the storage capacitor simultaneously. T2 will switch on and provide driving current to the LED pixel. After removed the select signal and data signal, the storage capacitor will hold the voltage of the gate of T2 during the whole display frame.

The operation points of the driving pMOS transistor and the LED pixel are shown in Fig.9(b). The driving transistor can provide output current as high as 45mA to the LED pixel, promising high brightness of the LEDoS panel for general displays and projection applications.

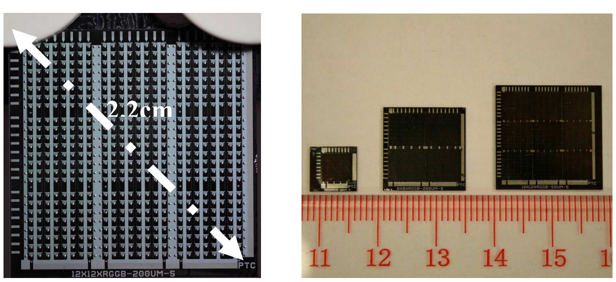
3.5 Scaling-up design to realize large area display

Full-custom designed active matrix substrates were designed to realize large area displays. The active matrix substrates had different numbers of zones and each zone was corresponding to one 8×8LED micro-array module discussed in Fig. 3. 4 LED micro-array modules were integrated onto a four-zone active matrix substrate to realize a 16×16 single color display panel or an 8×8 full-color display panel with a diagonal of 1.7cm; 9 LED micro-array modules were integrated onto a nine-zone active matrix substrate to realize a 24×24 single color display panel or a 12×12 full-color display panel with a diagonal of 2.2cm. Figure 10(a) shows a 24×24 active matrix substrate with solder bumps on each pixel circuit and Fig.10(b) shows the picture of 1 module, 4 modules and 9 modules integrated on active matrix substrates, respectively. The active matrix substrate can be designed maximum to 300mm (12-inch) on silicon substrate and meters on glass substrate. A real full-HD "LED TV" can be realized by increasing the numbers of the LED micro-array modules and the diagonal of the active matrix substrate. The detailed information of scaling-up designs is shown in Table1.



(a) (b)

Fig. 9 (a) Schematic of LEDoS pixel circuit and (b) operation points of driving transistor and LED pixel



(a) (b)

Fig.10 (a) 24×24 active matrix substrate with solder bumps on each pixel and (b) 1, 4, and 9 modules integrated on large area active matrix substrates

4. Conclusion

The first full-color active matrix programmable monolithic Light Emitting Diodes on Silicon (LEDoS) displays are fabricated using flip-chip technology. The forward voltage uniformity of the LED pixels was greatly improved by a double-side ground structure. A basic LED micro-array module was fabricated and the AM substrate has scaling-up ability. A large-scale display is obtained by integrating certain numbers of LED micro-array modules on full-custom designed active matrix substrates. Red, green and blue phosphors were excited by UV light to realize a full-color display. The LEDoS displays have excellent display uniformity, high brightness and individual controllability and suffcient driving capability.

Table 1. Scaling-up capability of the LEDoS displays

Module Num.	Resolution in single color	Resolution in full-color
1 (1×1)	8×8	4×4
4 (2×2)	16×16	8×8
9 (3×3)	24×24	12×12
…	…	…
(240×135)	1920×1080 (Full-HD)	960×540
…	…	…
(480×270)	3840×2160	1920×1080 (Full-HD)
…	…	…

5. Acknowledgments

This work was supported by the Innovation and Technology Commission (ITC) of Hong Kong Special Administrative Government (HKSAR) through NAMI, ITP/025/07NP. The author wants to thank the nanoelectronics fabrication facility (NFF), Epack Lab, and Suzhou institute of nano-tech and nano-bionics (SINANO) for their help on fabrication and packaging.

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