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Design and Fabrication of Fine-Pitch Pixelated-Addressed Micro-LED Arrays on Printed Circuit Board for Display and Communication Applications

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ABSTRACT In this paper, we report the design and fabrication of fine-pitch and pixelated-addressed micro-light emitting diode (LED) arrays with emission wavelengths of red (R), green (G), blue (B), and infrared (IR). The arrays have a resolution of 8×8 with monochromatic LED chips directly bonded to custom-designed printed circuit boards to form pixelated matrix. R, G, B, and IR micro-LED arrays with a pixel pitch of 1 mm were demonstrated. Sequential row scanning and multiple columns programming is performed by two CMOS-based application specific integrated circuit chips providing constant-sinking current and forward voltage for each pixel of the micro-LED arrays. The uniformity of operating current and forward voltage of the micro-LED pixels was measured with 1.94% coefficient of variation. The micro-LED pixel has much shorter rising time and higher response frequency than those of regular packaged blue and white LEDs. The implemented R–G–B micro-LED arrays are the excellent candidate for high-definition fine-pitch LED displays and demonstrated its versatile functionalities such as visible light communications. The IR micro-LED arrays show great potential in health medical treatment, IR detection imaging and local positioning system.

INDEX TERMS Micro-LED arrays, pixelated-addressed, display and communication.

I. INTRODUCTION

High efficiency III-Nitride-based light emitting diodes (LEDs) offer a wide variety of application such as flat-panel displays, solid-state lighting and striking signal lamp indications due to their excellent properties such as self-illumination, low power consumption, high brightness, long life-time and wide spectral regions [1]–[5]. Recently active matrix (AM) programmed silicon-based micro-LED displays by flip-chip (FC) bonding technology are attracting more attention. With a certain number of micro-LEDs fabricated onto Si-based substrate in matrix form, micro-LED displays have superior properties because of self-emitting, high light utilization ratio, and simple structure than traditional liquid crystal displays (LCDs) [6]–[10]. Complementary Metal Oxide Semiconductor (CMOS) transistors and optical interconnects were embedded in the substrate to provide the active matrix addressable signals to each micro-LED pixel. It has been well demonstrated that such monolithic integrations of AM micro-LED arrays have superior characteristics in improving pixel brightness and power efficiency, immunizing cross-talk problem, and reducing parasitic resistance and capacitance [11]. Constant efforts have been investing for scaling down the pixel pitch and increasing the display resolution of micro-LED displays.

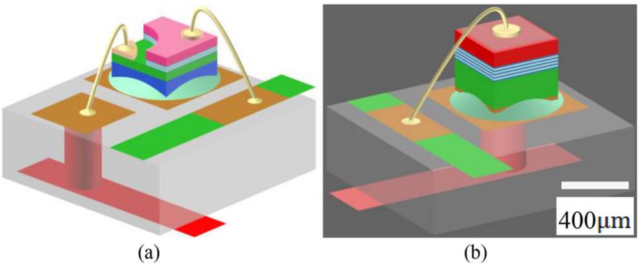
However, the reported monolithic integrated AM micro-LED displays required complicated microelectronic fabrication process and followed sophisticated verification rules [2], [7], [10]. AM micro-LED display on silicon is for high resolution and high content display applications, while the PM micro-LED display on PCB made by the technology in this work is potentially applied for low resolution and low end display applications. [12]–[14]. It is a fast, low cost and high efficiency way in fabricating fine pitch micro-LED displays to directly bond discrete LED devices to printed circuit board with peripheral ASIC chips pixelated addressable driving methods [15]–[17].

In this work, we designed and fabricated 8×8 micro-LED arrays with R, G, B and IR LEDs respectively and directly bonded the arrays onto customized PCBs by chip on board (CoB) technology. Two CMOS-based ASIC chips were matched to address each pixel of the micro-LED arrays in a sequential row scanning and multiple columns programming pattern. The sizes of blue, green, red and IR LEDs are 230µm×385µm, 210µm×210µm, 225µm×225µm and 285µm×285µm, respectively. The implemented micro-LED arrays have excellent quality in both uniformity of operating current and rising time of step response. The R, G, B micro-LED arrays can be used to show representative letters or animations, simulate visible light communication (VLC) [18], [19] and serve as tricolor light source of the full-color LED projector [20]. The IR micro-LED arrays at 850nm also have valuable utilization in positioning system [21] and imaging in human tissues [22].

II. EXPERIMENT

A. DESIGN AND FABRICATION OF THE MICRO-LED ARRAYS

According to the original growth substrates, LED devices have two basic structures: lateral structure and vertical structures. The p- and n- electrodes are located at the same side of the lateral LED devices. Operating currents are transversely flowing in the n- and p-type GaN layers. The two electrodes of the LED devices with vertical structure are respectively located at top and bottom of the LED epitaxial layers, so that the currents almost entirely flow past the LED epitaxial layer. Based on the LED device structures, a customized PCB was designed and fabricated which can be employed universally for both structures. Fig. 1. (a) is a schematic diagram of a lateral pixelated LED, metal column and row lines were etched on the PCB's upper and lower surfaces respectively in vertical distribution. In order to establish mechanical and electrical connection of LED devices on the upper surface of the PCB in minimum area, each pixel was drilled a via-hole to connect the contacts to the upper surface. Then metallic square contact pads were etched as n-bonding area of the LED devices above the via-hole, and rectangle opening windows were designed as p-bonding area upon each column line. After cleaning the PCB with deionized water and drying process, a die bonder machine was employed to dispense the liquid conductive silver colloid to the designated contact of each pixel on PCB, and then pick up a LED device from the expanded blue film and put it on the liquid conductive silver colloid. Repetition goes on until all the 64 LEDs were fixed on the PCB in matrix form. Then the micro-LED arrays were cured in oven for 2 hours with temperature of 150°C. The lateral LED devices' electrodes were connected to n- and p-contact pads respectively towed by 20µm gold wires using ultrasonic bonding instrument. The vertical LED device was directly fixed upon the via-hole through conductive silver colloid to complete its n-electrode connection and its p-electrode was connected to p-contact by gold bonding wire as shown in Fig. 1. (b). All metallic contacts and opening windows were plated by gold in thickness of 2 mil using immersion gold plating (IGP) technique in order to obtain better contacting effect.



(a) (b)

FIGURE 1. Schematic diagram of (a) a lateral LED pixel and (b) a vertical LED pixel.

B. DRIVING SCHEME OF THE MICRO-LED ARRAYS

Since the red, green, blue, and IR LED devices were die-attached and wire-bonded onto the PCB panels in matrix mode, a sequential row scanning and multiple columns programming is employed to parallel address the micro-LED arrays. Fig. 2 shows the driving principle of a constant current driver and a matched column driver for illumination of the micro-LED arrays, including an example within three data frames and a display sample.

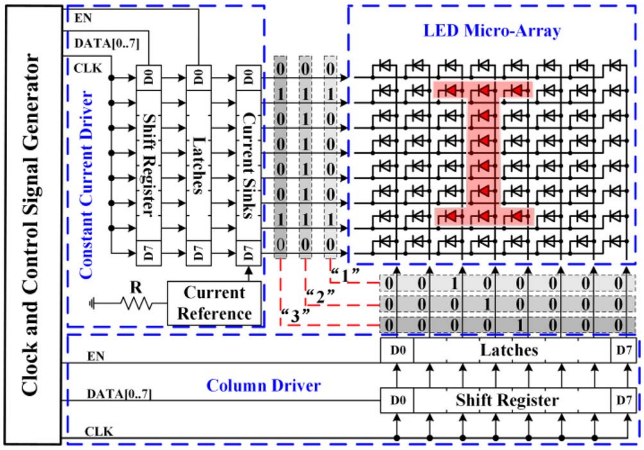


FIGURE 2. Driving principle of the micro-LED arrays with sequential row scanning and multiple columns programming.

A field programmable gate array (FPGA) board was developed to provide clock and control signals to the two matched CMOS drivers. As illustrated in Fig. 2, the column driver and MCCS driver based on serial-input and parallel-output (SIPO) structure are operating under the same clock (CLK). The 8-bit shift register (SR) clocked at 1kHz in the column driver generates column selection signals and constant-current data to conduct LEDs in a column with selection. The basic operation of single addressing scheme is described as follows. Firstly, two packets of 8-bit data were generated by FPGA board and then synchronously shifted into the shift register of column driver and MCCS driver from most significant bit (MSB) to least significant bit (LSB), respectively. Then, the latch signal EN releases the latch before the next clock rising edge to make column selection signals and current data. After that, the next packet of data will repeat the first step and it will not affect the output until the next release signal EN is triggered. For example, the constant-current driver outputs '01000010' and column driver outputs '00100000' at the third frame, '01111110' and '00010000' at the forth frame, '01000010' and '00001000' at the fifth frame, respectively and synchronously. If the frame cycle scan period is faster enough than the effect of persistence of vision, the micro-LED arrays will display a result of 'I' in no blinking status.

III. RESULT AND DISCUSSION

Fig. 3 shows the optical emission spectrum measurement results of blue, green, red and IR micro-LED pixels with a peak wavelength of 460nm, 572nm, 630nm and 850nm, respectively. Their full wavelengths at half maximum (FWHM) are all less than 30nm. Fig. 4 shows the I-V characteristics of one LED pixel of R, G, B and IR micro-LED arrays. The forward voltage of the R, G, B and IR LED is approximately 1.8V, 2.8V, 3.3V and 1.35V respectively with a forward current of 10mA.

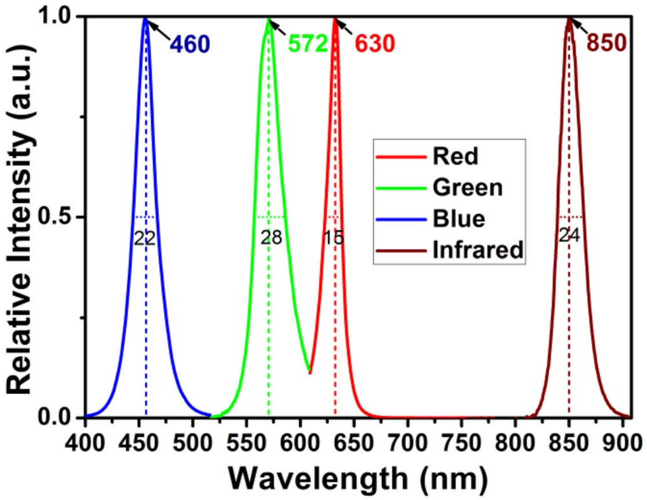


FIGURE 3. Optical emission spectrums of blue, green, red and IR micro-LED pixels.

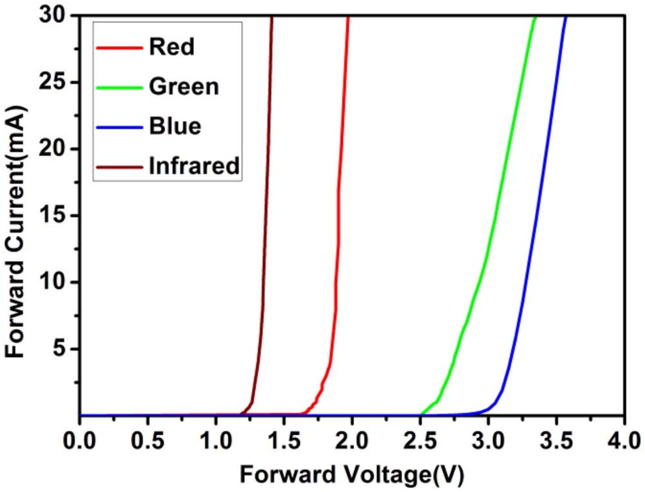
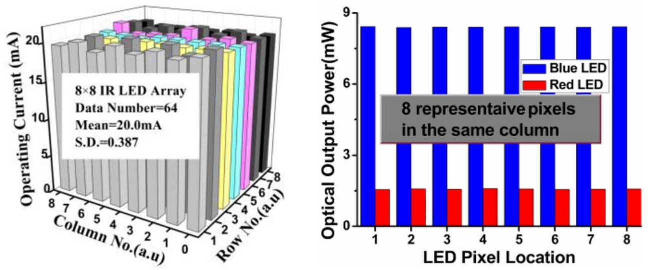


FIGURE 4. I-V characteristics of one LED pixel of R, G, B and IR micro-LED arrays.



(a) (b)

FIGURE 5. (a) Operating currents of 8×8 IR micro-LED array with 1.4V forward voltage (b) Optical output power of 8 representative pixels under 20mA injection current in the same column of blue and red micro-LED arrays.

With 1kHz clock frequency and 20mA operating current, the 8×8 IR micro-LED array with 1.4V forward voltage was measured by a digital power meter as shown in Fig. 5. (a). Due to the discreteness of CMOS components and measurement error, the sinking currents of each column in different location have a slight difference. Nonetheless it can be seen that the mean current of 64 IR LEDs is 20.0mA and the standard deviation (SD) is 0.387, corresponding to a 1.94% coefficient of variation. It means that the driving system has consistent current outputs to each pixel of the micro-LED arrays. Optical output powers of 8 representative pixels under 20mA injection current in the same column of blue and red micro-LED arrays were also measured as shown in Fig. 5. (b). Optical output powers of pixelated blue and red LED are around 8.4mW and 1.55mW respectively.

After downloading program to the FPGA board, the R, G and B micro-LED arrays can exhibit representative letters ("EPIL" shown in Fig. 6. (a)). The visible color micro-LED arrays implemented in this work can not only be used in static or dynamic monochrome displays, but also in full-color projection and visible light communication system (VLCs). IR micro-LED array was demonstrated by an infrared camera to present two images as shown in Fig. 6. (b). More specially, the emission wavelengths of IR micro-LED arrays were in invisible range. Therefore an infrared camera was used to take two representative photographs of the implemented IR micro-LED arrays because the acceptable spectrum range of the photosensitive element inside the infrared camera is broader than human eyes.

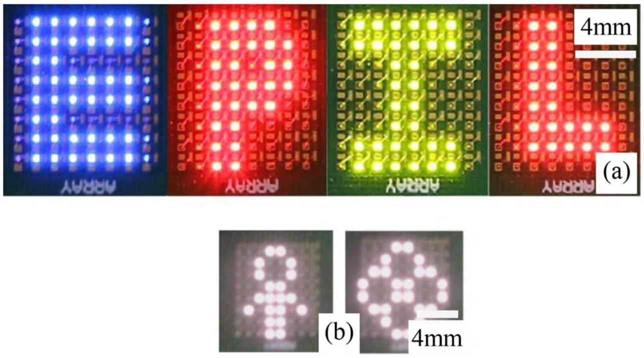
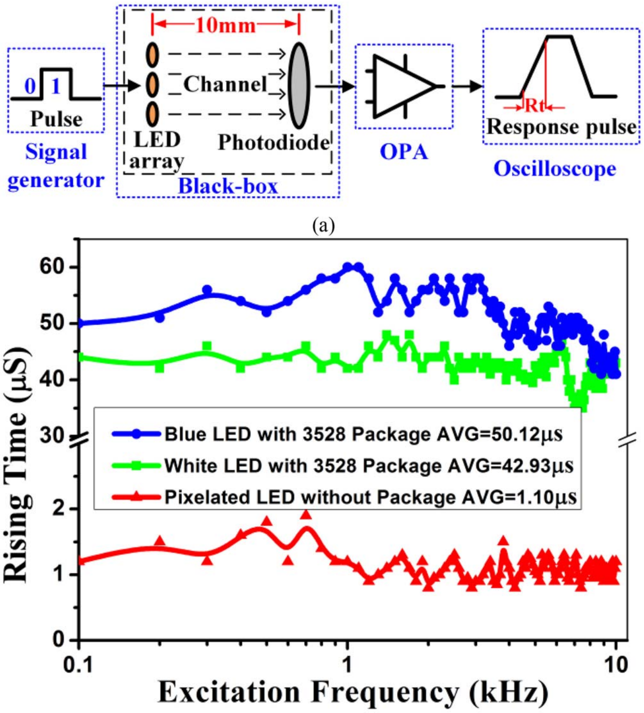


FIGURE 6. Representative display results of 8×8 micro-LED arrays with emission color of (a) R, G, B and (b) IR.

VLCs using LED as a light source is a potential technology for short range and high-speed indoor wireless transmission networks. Based on the principle of modulation and demodulation, a VLC system consists of at least a LED emitter and an optical receiver. One of the critical factors of VLCs with LEDs is the rising time of step response, which can directly affect the transmission rate and bandwidth of the VLCs. In this work, we have investigated the frequency response of pixelated micro-LED pixel and LEDs with standard package as shown in Fig. 7. (a). Pulse signals were generated by signal generator to drive the LED, and the photodiode was used to detect incident light. Photocurrents were produced by the photodiode and amplified by the operational amplifier (OPA) circuits. Then the amplified output pulses were sampled by an oscilloscope and the rising times (Rt) were obtained. The bandwidths of photodiode, OPA and Oscilloscope were 100kHz, 1.2MHz and 1GHz, respectively. The input voltage amplitude was 3.3V and its duty cycle was 50%. It must be noted that the LED and the photodiode were placed in the black-box to prevent ambient light interference. And the Rt was defined as the time from 10% to 90% of peak-peak value at the rising edge.

Pixelated LEDs of the micro-LED arrays without package, blue LED and white LED with 3528 package were employed to measure their Rt using the experimental setup mentioned previously. Fig. 7. (b) shows the measurement results of Rt when giving excitation pulse frequency to these three kinds of LEDs from 100Hz to 10kHz with a 100Hz step. The average (AVG) rising times of blue and white LED with 3528 package and pixelated LED of micro-LED array without package are 50.12μs, 42.9μs and 1.10μs respectively. Compare with the huge 3528 packaged LEDs, micro-LED array can greatly reduce the parasitic resistance and capacitance. So the response frequency can be greatly increased as well as the transmission rate and bandwidth.



(a)

(b)

FIGURE 7. (a) Experimental setup for measuring the rising time (Rt) of the micro-LED arrays based on step response (b) Experimental results of Rt using white and blue LED with 3528 package and blue pixelated micro-LED array without package as the light source respectively.

The micro-LED array size and resolution can be extended with stitching multiple micro-LED arrays. However, it is fairly difficult for the pixel pitch to make a breakthrough to achieve a smaller pitch under 300μm due to the pixel two-dimensional size and wire-bonding machine. In addition, metal contact and via-hole in each micro-pixel of the micro-LED arrays can provide heat dissipation to the LED devices in a certain degree. That means the proposed micro-LED arrays can be also applied in array package of mid- and high-power LED devices.

IV. CONCLUSION

8×8 micro-LED arrays with R, G, B and IR LEDs respectively and directly bonded the arrays onto customized PCBs by chip on board (CoB) technology were presented in this work. Sequential row scanning and multiple columns programming is performed by two CMOS-based application specific integrated circuit (ASIC) chips to address the pixels of the micro-LED arrays. The proposed R-G-B micro-LED arrays can be used in fabricating high-definition fine-pitch display module. When working under a standard reference current (20mA), uniformity of operating current of the micro-LED pixels was measured with 1.94% coefficient of variation. Response rise-time of the micro-LED arrays is shorter than those LEDs packaged in 3258 form, the micro-LED arrays will consequently obtain higher bandwidth and transfer speed of data when applied in VLCs.

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