Investigation of Forward Voltage Uniformity in Monolithic Light-Emitting Diode Arrays

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***Abstract*— This letter reports the design and fabrication of optimized electrode structures for matrix addressable monolithic light-emitting diode arrays. The variation of forward voltages of LED pixels in the same row are greatly reduced from 2.62 V (81.9%) to 0.02 V (0.6%) in an 8×8 LED array. The LED arrays are designed with 8×8 square pixels, 500×500 μm^2 with a 50-μm wide gap in between. A 24×24 large-scale blue LED panel is demonstrated with 0.06V (1.8%) forward voltage variation by integrating nine LED array modules on a 2.2-cm diagonal silicon-based substrate. With a similar concept, a 30×30 green LED micro-display with scaled pixel pitch shows excellent display uniformity.**

***Index Terms*— Gallium compounds, light-emitting diodes, arrays, flip-chip devices.**

I. Introduction

LED arrays made of individually packaged devices have diverse applications due to their superior characteristics such as longer lifetime, higher contrast, and better visibility under bright sunlight compared to liquid crystal and organic light emitting diode (OLED) displays. Recently, several techniques have been developed to fabricate monolithic LED arrays [1], [2]. Pixels in the same row or column usually share a common n-electrode. However, since path resistance depends on the wire distances between each LED pixel and the common n-electrode, different voltage drops would occur across each LED in the same row at constant injection current. The variation of forward voltages could cause a drift of operation points between the LED pixel and the driving circuit, resulting in poor display quality due to the variation of brightness among LED pixels [3], [4]. At present, 2-inch sapphire and SiC wafers are widely used for epitaxial growth of III-nitride based LEDs. The utilization rate of wafer area is undesirably low for LED arrays with relatively large dimensions (typically several millimeters diagonal). Hence, before the scale-up of sapphire and SiC substrates become commonplace, it is necessary to combine small-sized LED arrays in order to obtain larger arrays. When LED arrays are scaled-up, electrical uniformity such as forward voltages of the LED pixels will be very important for a high quality display. Sophisticated driving circuits and optical designs were developed to compensate for such variations in order to improve the display quality [5]–[9]. An alternative method is to optimize the layout design for better uniformity.

In our previous publications reporting 8×8 active matrix LED arrays, we measured a maximum forward voltage variation across LED pixels in the same row to be 0.4V [10]. In the current publication, the above variation was systematically investigated. The uniformity of 8 LED pixels in the same row was greatly improved by optimizing the device structures and the layout. Then 8×8 LED array modules were fabricated on sapphire substrates and then bonded onto silicon-based substrates using the flip-chip technique. Flip-chip bonding provides a convenient solution to integrate standard LED array modules on custom-designed silicon substrates commercially available in 12-inch size. Novel designs were implemented on the substrates for integration of a number of LED array modules to realize high-resolution and large-scale panels with good forward voltage uniformity.

II. Device Design and Fabrication

In our previous study, the forward voltage uniformity was improved in a design with n-metal bus lines on one side for each row. The forward voltages varied from 3.30V to 3.70V over the entire row under the same 20mA injection current [10]. In the present work, 8×8 LED arrays were designed as a basic module for large-scale LED arrays as shown in Fig.1 with four different designs. The n-electrodes of each row were placed at two sides of the LED array. The two n-electrode columns were connected to the corresponding cathode terminals of the silicon-based substrate. The independent p-electrode of each LED pixel was connected to the corresponding anode on the silicon-based substrate by solder bumps. In design (a), 8×8 LED pixels formed an array without any design optimization and the current between the pixels flows through the n-GaN layer. In design (b), a 50μm wide n-metal line was added as an extension of the common cathode for each row. In design (c), the n-metal line was a wrap-around design for each LED pixel. In design (d), double-sided cathodes were used as well as n-metal wrap-around. With the n-metal wrap-around and double-sided cathodes designs, the path resistance of each LED pixel decreased, and significant improvements in current flow and forward voltage uniformity were realized.

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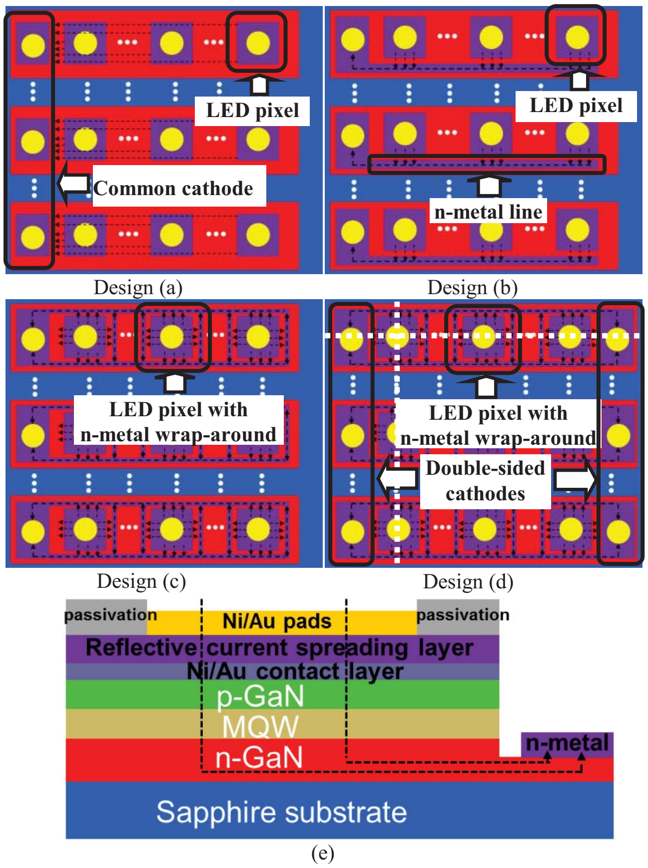

Fig. 1. (a) Design without any electrode optimization; (b) Design with 50μm wide n-metal line; (c) Design with n-metal wrap-around; (d) Design with n-metal wrap-around and double-sided cathodes. Only a part of the pixels of the 8×8 LED arrays are shown. The black dashed lines show the current flow of the LED pixels. (e) Shows the layer structure of the blue and green LED pixels. The black dashed lines show the current flow from the Ni/Au pads on the p-electrode to the n-metal.

The silicon-based substrate consisted of 8×8 solder bumps aligned coherently with the LED array to provide current flow through each pixel. N-metal wrap-around and double-sided cathodes configurations were designed to eliminate the forward voltage variation of LED pixels in the array. A scaled-up structure was designed with 4-zone and 9-zone areas, respectively. Each zone corresponded to a standard LED array module. By integrating 4 and 9 LED array modules on the substrate using a flip-chip process, a 16×16 panel 1.7cm diagonal and a 24×24 panel 2.2cm diagonal were fabricated.

Standard multiple quantum well (MQW) LED wafers grown on sapphire substrates were used to fabricate the LED arrays and the detailed layer structure can be found in Fig. 1(e). Silicon dioxide (SiO_2) was used as hard mask for dry etching. The LED wafers were etched all the way down to the sapphire substrate to isolate each row. SiO_2 mask and dry etching were used to define the mesa structure of each LED pixel. A thin Ni/Au (5/5nm) layer was deposited by electron-beam evaporation [11]. Annealing in atmospheric ambient at 570°C for 5 minutes was performed to improve the ohmic contact and the adhesion between Ni/Au contact layer and p-GaN layer. Subsequently, Ti/Al/Ti/Au (30/120/10/30nm) multi-layers were evaporated to form the n-electrode that also served as a reflective current spreading layer on the Ni/Au contact layer. Finally, a SiO_2 passivation layer was deposited. Openings in the SiO_2 were defined and Ni/Au (500/30nm) pads were formed in the opening for flip-chip bonding to the p-electrodes on the Si substrate.

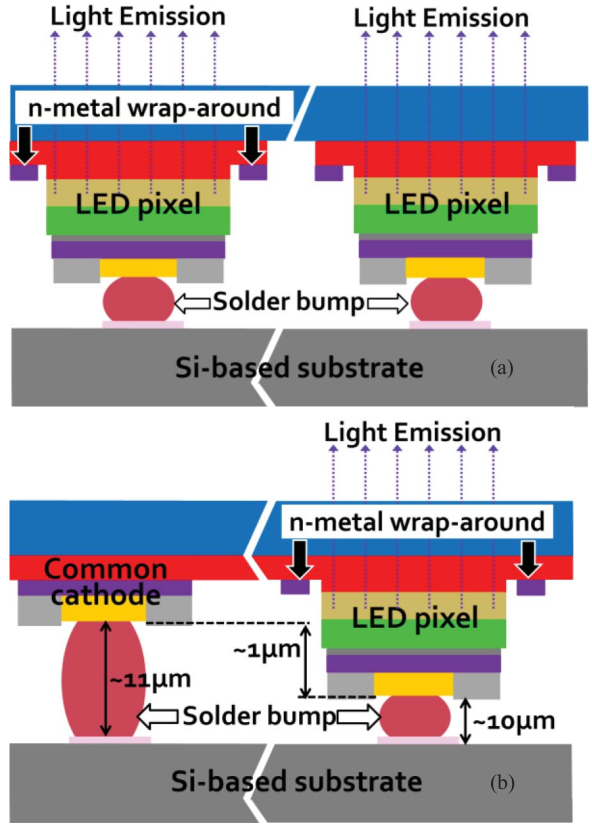

Fig. 2. Cross-sectional view of the LED pixels flip-chip bonded on silicon-based substrate along (a) the vertical white dashed line and (b) the lateral white dashed line in Fig. 1 (d).

Process of the silicon-based substrate started with (100) single crystal silicon wafers. A layer of SiO_2 was deposited to provide isolation. Then aluminum-1%silicon alloy was deposited and patterned as internal connection lines. Another layer of SiO_2 was deposited for passivation and patterned. TiW/Cu (30/500nm) seed layers were deposited and photo-resist AZ4903 was coated and patterned. A thick Cu layer (8μm) and a Tin-Lead layer (22μm) were deposited by electroplating. After an annealing process in a reflow furnace, uniform solder bumps were formed in ball shape. The LED array wafer was thinned and diced. Finally the diced LED array was flipped onto the silicon-based substrate, as shown in Fig.2. During flip-chip bonding, solder bumps conformed and compensated the 1μm difference in height (see Fig. 2 (b)) between the pads on the reflective current spreading layer and the cathodes.

III. Results and Discussion

Forward voltages of the 8 LEDs in the same row of the four designs were measured. Comparison results of forward voltage variation are shown in Fig. 3(a). The variation of the initial design was 2.62V, up to 81.9% of the base voltage 3.2V.

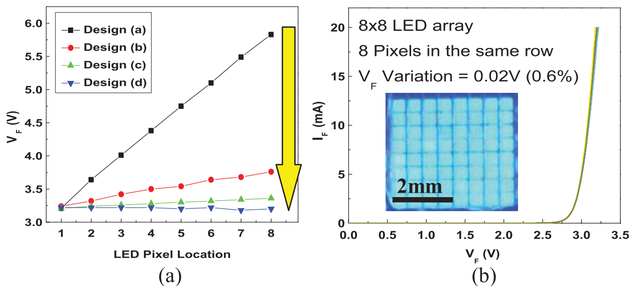

Fig. 3. (a) V_F variation of 8 LEDs in the same row of different designs. The V_F of design (d) exhibits excellent uniformity with maximum variation smaller than 0.02V. (b) I–V curves of 8 LED Pixels in the same row of design (d). Inset shows operating 8×8 LED array module.

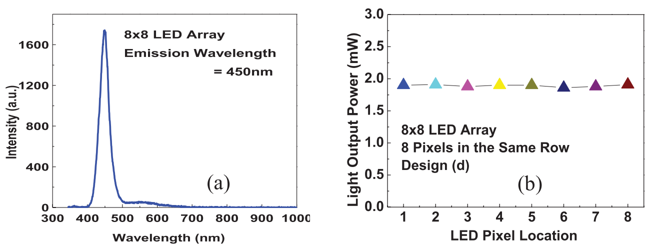

Fig. 4. (a) PL wavelength and (b) EL light output power of the 8 LED pixels in the same row of design (d).

With the 50μm wide n-metal line, the variation was decreased to 0.52V (16.3%). With n-metal wrap-around design, the variation was further reduced to 0.15V (4.7%). In design (d), when both n-metal wrap-around and double-sided cathodes were adopted, the variation of the forward voltages of the 8 LEDs was significantly reduced to 0.02V (0.6%). Fig. 3(b) shows current-voltage (I–V) characteristics of the 8 LED pixels in the same row of design (d). From the powered display result (see inset of Fig. 3 (b)) of the LED array module of design (d), the 8×8 LED array module has a good display uniformity and brightness, making it a promising candidate for a broad range of optical applications.

Fig.4 (a) shows the photoluminescence (PL) measurement result of the LED pixels. Fig. 4 (b) compares the electroluminescence (EL) measurement results of 8 LED pixels in the same row of design (d), showing that the optimized structure resulted in uniform light output power over the 8 LED pixels.

Large-scale LED arrays were demonstrated by integrating 4 and 9 pieces of 8×8 LED array modules on a corresponding silicon substrate. The finished LED array prototypes in different sizes are shown in Fig. 5 (a). From left to right, an 8×8 LED array module, a 16×16 LED array 1.7cm diagonal, and a 24×24 LED array 2.2cm diagonal are displayed. The forward voltages of the 24 LED pixels in the same row exhibited good uniformity with a variation of 0.06V (1.8% of the base voltage 3.2V) as shown in Fig. 5 (b). The LED array designed in this letter provides a promising method for LED array binning, and also improves the utilization rate of LED wafers. It clearly demonstrates the feasibility of achieving high-resolution and large-scale LED arrays with excellent forward voltage uniformity.

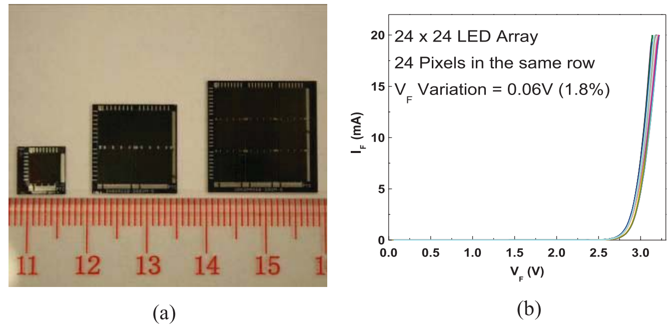

Fig. 5. (a) One, four and nine LED array modules were integrated on silicon-based substrates; (b) I–V curves of 24 LED pixels in the same row of the 24×24 LED array. The V_F variation was measured to be 1.8% of the base voltage 3.2V.

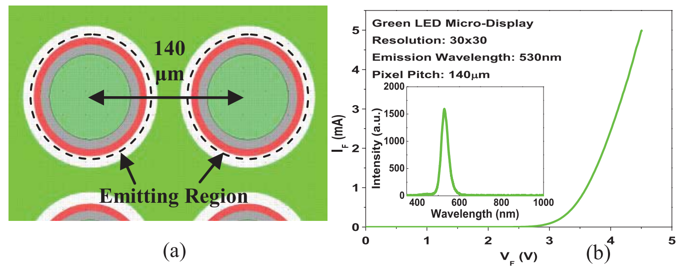

Fig. 6. (a) Pixel layout of green LED pixels using the n-electrode wrap-around concept. The green area inside the emitting region is p-electrode area and the green area outside the emitting region is n-electrode area; (b) I–V characteristics of green LED pixels. Inset shows PL result with an emission wavelength of 530nm.

Scaled green LED micro-displays with small pixel size were also designed and fabricated using the optimized n-electrode wrap-around concept as shown in Fig. 6 (a). The micro-display has a resolution of 30×30 and a pixel pitch of 140μm. I–V characteristics of the green LED pixel are shown in Fig. 6 (b). The variation of forward voltages in the same row with the same 5mA injection current was measured to be ±5% of base voltage 4.5V. Inset of Fig. 6 (b) shows PL measurement result of the green LED pixels with peak emission wavelength of 530nm. The micro-LED pixels were designed in circular shape with a diameter of 100μm. Except the light emitting region in each pixel, the surrounding area was covered with n-electrode metal to reduce the forward voltage variation among the 30 LED pixels in the same row.

The green LED micro-display was programmed by a periphery driving board with PIC32MX795F MCU controller. Representative images (HKUST logo shown in Fig. 7) and animations can be programmed, demonstrating uniform display result. Due to color saturation under the microscope, the bright pixels in the figure appear to be white. Note that the metal inter-connection lines around dark pixels reflect partial light emitted from neighboring bright pixels. A black matrix layer will be coated and patterned in future improved version to prevent light reflectance of the metal lines for a better display contrast. The LED micro-display with uniform forward voltage has potential applications in the area of portable displays, pico-projectors, bio-medical sensors and visible light communication.

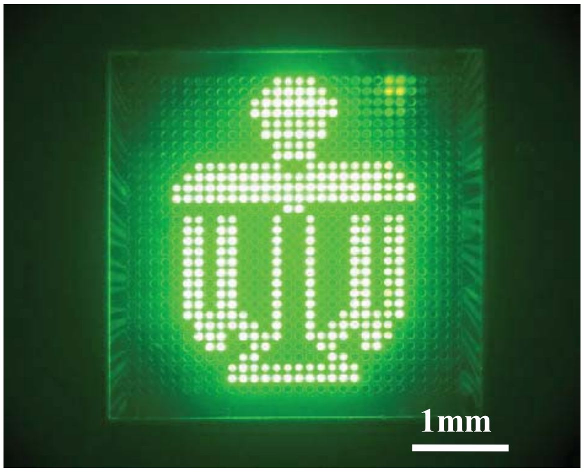

Fig. 7. Representative display image of the 30×30 green LED micro-display.

IV. Conclusion

Optimized structures were designed and fabricated to reduce the variation of the forward voltages in III-nitride based LED arrays. With wrap-around n-metal and double-sided cathodes design, the variation of the forward voltages of 8 LED pixels in the same row was reduced from 82% to 0.6%. A 24×24 large-scale blue LED array 2.2cm diagonal was demonstrated by integrating 9 LED array modules on a full-custom silicon-based substrate. 24 LED pixels in the same row had uniform forward voltages with variation of 1.8%. The optimized n-electrode structure was also successfully applied to a scaled green LED micro-display with good display uniformity.

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