Gallium Nitride Blue/Green Micro-LEDs for High Brightness and Transparency Display

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***Abstract*— GaN-based Micro-LED has become a research hotspot as a novel display technology due to its numerous unique advantages. Especially in augmented reality and smart glasses applications, Micro-LED display chip with high transparency possesses unparalleled opportunities. In this work, GaN-based transparent single-color Micro-LED display chip based on double-side polished sapphire substrate was designed with a single pixel size of 20 μm×20 μm, and a resolution of 254 pixel per inch (PPI). The transparency reaches 80% among the whole display area ~ 0.18 inch, and the luminance of display chip can reach up to 25000 nits. It demonstrates a broad application prospects in augmented reality, smart glasses, and etc., providing promising vista for the development of "Metaverse" in the future.**

***Index Terms*— Micro-LED, transparent display, GaN.**

I. Introduction

SINCE its first debut in the 1990s, the GaN-based semiconductor light-emitting diodes (LED) have been widely used in solid-state lighting illumination applications after decades of development [1], [2]. In recent years, LEDs with micro-size have been evolved toward the new society of display for the next generation, leading to a booming emergence of micro self-emissive display industry [3]. At present, Micro-LED is widely considered as one of the most promising novel display technology with a great potential for applications in virtual reality (VR) [4], [5], [6], [7], augmented reality (AR) [8], [9], [10], [11], optical communication [12], [13], [14], [15], [16], biomedical probes [17], [18], [19], and etc.

Monolithic Micro-LED displays have been reported since 2011 [20]. To date, most monolithic Micro-LED displays require flip-chip bonding with silicon-based complementary metal oxide semiconductor (CMOS) or thin film transistor (TFT) driving circuits to realize pixel control [21], [22]. Such Micro-LEDs are capable of fulfilling traditional panel display applications. But in recent years, new display applications, such as AR [23], [24], [25], [26], and [27], smart glasses, head up display (HUD), etc., have raised new requirements for displays, focusing on the following aspects: (1) high transparency; (2) high luminance. Due to the light-absorbing property of silicon, traditional silicon-based monolithic Micro-LED displays are obviously unable to meet the demands of transparent display applications.

To achieve transparent displays, researchers have proposed several solutions. One is to transfer sapphire-based or silicon-based Micro-LEDs onto a glass substrate and bond with TFT driving circuits [10], [28], [29]. This solution can achieve a good display performance. But it requires huge amounts transfer of Micro-LEDs (i.e. mass transfer), which is time-consuming and no guarantee of high yield. Another feasible option is to project the pattern onto the transparent glass panel by means of optical waveguide. The significant disadvantage of this method is the severe loss of luminance, which is essential for transparent displays working in outdoor environments.

In this work, we designed and fabricated GaN-based Micro-LED display on sapphire substrates with high transparent properties, of which the optical transmittance can be as high as 80% among the whole display area. It has basically reached the theoretical upper limitation of Micro-LED display transparency [30]. In comparison, the transparency of Micro-LED displays currently reported by professional Micro-LED companies is only 48% (by PlayNitride Inc.) [30] and 70% (by Xceleprint Inc.) [10]. The entire display array consists of 1024 pixels, and the size of a single pixel is 20 μm×20 μm. The display area has a dimension of approximately 0.18 inch, with a resolution of 254 PPI, and the brightness can reach up to 25000 nits, which satisfies the demand of display

Manuscript received 30 November 2022; accepted 5 December 2022. Date of publication 12 December 2022; date of current version 27 January 2023. This work was supported in part by the National Key Research and Development Program of China under Grant 2021YFB3601600; in part by the National Natural Science Foundation of China under Grant 62074077, Grant 62004104, Grant 61974062, and Grant 61921005; in part by the Leading-edge Technology Program of Jiangsu Natural Science Foundation under Grant BK20202005 and Grant BE2021008-2; in part by the Fundamental Research Foundation for the Central Universities; and in part by the Solid State Lighting and Energy-saving Electronics Collaborative Innovation Center. The review of this letter was arranged by Editor T.-Y. Seong. *(Corresponding authors: Tao Tao; Bin Liu.)*

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Color versions of one or more figures in this letter are available at https://doi.org/10.1109/LED.2022.3228529.

Digital Object Identifier 10.1109/LED.2022.3228529

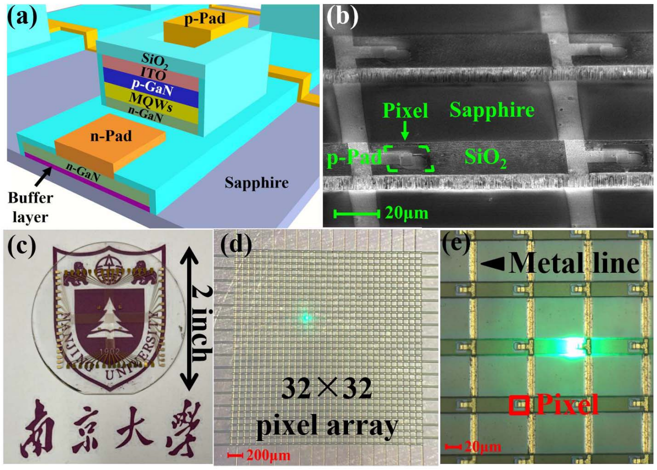

Fig. 1. (a) Schematic diagram of a transparent Micro-LED display. (b) SEM image of the display after fabrication, corresponding to Fig.1a. (c) Complete 2-inch transparent Micro-LED display after fabrication. (d) Microscope image of the display array, about 3.2 mm in dimension. (e) A single working Micro-LED pixel.

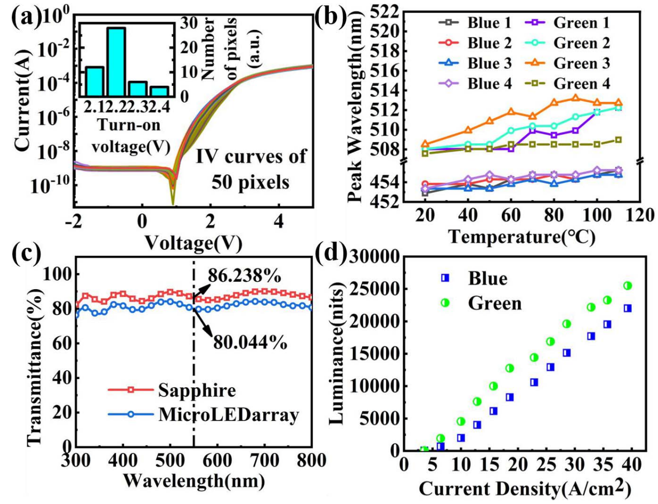

Fig. 2. (a) I-V curves of randomly selected 50 Micro-LED pixels, and the inset shows the turn-on voltage statistics for 50 pixels. (b) Peak shift of luminescence of blue and green pixels with respect to the temperature. (c) Transparency of the Micro-LED display chip and sapphire substrate. (d) The luminance of blue and green Micro-LED display chip.

applications in outdoor environments. All pixels are driven by passive matrix (PM) driving circuit, and the display images are demonstrated in this work. Our work could promote the applications of transparent display technology in new fields such as AR and smart glasses, inspiring cooperation and innovation in the industry.

II. Fabrication of Transparent Micro-Led Display

Figure 1a illustrated the schematic diagram of a transparent Micro-LED display. As shown, a matrix of 32 × 32 Micro-LED array with a pixel size of 20 μm and a pitch of 80 μm were designed and fabricated. The GaN LED epitaxial wafers were grown on a double-side polished sapphire substrate by metal-organic chemical vapor deposition (MOCVD). The epitaxial structure was designed for display applications, which consists of a 3-μm-thick GaN buffer layer, a Si-doped n-type GaN layer, 8-period multiple quantum wells (MQWs), and a Mg-doped p-type GaN layer. A 100 nm thin indium tin oxide (ITO) was deposited on top of the p-GaN layer to improve the Ohmic contact of p-electrodes. Each pixel was defined and fabricated by microfabrication processes including lithography, reactive ion etching (RIE), and inductively coupled plasma (ICP) etching. A 1μm-thickness SiO_2 layer was deposited covering each face of the pixel using plasma enhanced chemical vaper deposition (PECVD) for electrical isolation. Subsequently, Ti/Al/Ni/Au electrodes were deposited on each pixel by electron beam evaporation (EBE). The scanning electron microscope (SEM) image of the display array is shown in figure 1b, of which the structure is consistent with that in figure 1a. The entire display region is a square of approximately 0.18 inch and contains 1024 pixels with a resolution of 254 PPI.

Figure 1c shows a 2-inch transparent Micro-LED display chip. The display area can be seen by the microscope image in figure 1d. In the array, the n-type electrodes of each row of pixels and the p-type electrodes of each column of pixels are connected. At the edge of the display array, electrode lines are extended and connected to the peripheral driver circuit. By applying optimized bias between rows and columns, each pixel can be lit up individually. Figure 1e illustrates an image of a single working pixel. It can be seen that a certain range around the pixel, in addition to the pixel itself emitting light, is also illuminated. This phenomenon is caused by the multiple reflections of light within the transparent substrate, namely light crosstalk, and may have negative influence on the performance of display. Much work should be done for the sake of reducing the influence of light crosstalk in the future.

Fig.2 (a) I-V curves of randomly selected 50 Micro-LED pixels, and the inset shows the turn-on voltage statistics for 50 pixels. (b) Peak shift of luminescence of blue and green pixels with respect to the temperature. (c) Transparency of the Micro-LED display chip and sapphire substrate. (d) The luminance of blue and green Micro-LED display chip.

It is vital to acquiring high yield in optical and electrical performance in display, as shown in figure 2a, the current-voltage (I-V) curves of randomly selected 50 Micro-LED pixels indicate good operating yield with relatively high uniformity. The inset of figure 1a shows the turn-on voltage statistics for 50 pixels, indicating that the average turn-on voltage of the pixels is about 2.2 V. Meanwhile, the reverse leakage current is less than 1 nA (@-1.5 V), showing a good electrical passivation on the sidewall of each pixel. There is small difference in I-V curves under the bias ranging from 1 V to 3 V, which is mainly attributed to the forward current leakage. There are two main causes. One is that the LED epitaxial layer grown by MOCVD is not that uniform at different positions. The other reason is that there are unavoidable small differences caused by fabrication process among pixels, resulting in variations of pixel performance. Nevertheless, these differences have little impact on the performance of the display and can be settled by optimization.

Figure 2b demonstrates the peak shift of luminescence of blue and green pixels with respect to the temperature. Four blue and four green pixels were randomly selected, powered by a constant current of 250 A/cm^2 (to prevent the current shift caused by changed temperatures), and measured the EL peak shift from room temperature 20 °C to 110 °C. The results show that the emission peaks of blue and green pixels have red shift of about 2 nm and 4 nm, respectively. The reason for the red-shift of the luminescence peak is that the change of the forbidden band width of the III-V group nitride semiconductor material with temperature can be described by the following Varshni formula:

$$E(T) = E(0) - \frac{\alpha T^2}{T+\beta} - \frac{\alpha^2}{k_B T}$$

Among them, $E(T)$ is the forbidden band width at different temperatures T, $E(0)$ refers to the forbidden band width value at 0 K, α and β are Varshni thermal coefficients, and σ represents the degree of localization [31]. According to the fitting result by such formula, at higher temperature, the forbidden band width of III-V nitride materials shows a decreasing trend with the increased temperature, which means a reduction of the quantum well band gap of Micro-LED devices, resulting in red shift of the luminescence peak in the spectrum [32]. For displays, it is very important to maintain the stability of color emitted by the pixels at different operating temperatures. Apparently, our display exhibits a relatively good stability in luminescence wavelength at different temperatures.

Figure 2c shows the transparency test result of the sample. In order to characterize the overall transparency of the sample, the median of the test wavelength range, that is, the light transmittance at 550 nm, was used for characterization. It can be observed from the figure 2c that the light transmittance at the position of the Micro-LED array reaches 80.044%, which is only about 6% lower than that of the original sapphire substrate. We believe that our Micro-LED display chip has excellent transparency and can well meet the demands of transparent display applications. Figure 2d illustrates the brightness of blue and green Micro-LED display chips measured by a spectroradiometer (MINOLTA CS-2000). Note that the luminance here refers to the luminance of the entire operating display, rather than the individual pixel. Both current and brightness were normalized by the area of the Micro-LED display. For GaN-based Micro-LED display chip, the luminance can easily acquire 10000 nits, and the maximum luminance will reach 25000 nits at the current density of 40 A/cm^2 in the test. Such high brightness can support numerous types of applications including AR/VR glasses, head up display (HUD) under daylight and sun shine.

III. Driving System of the Transparent Micro-LED Display

In order to realize the image display, the Micro-LED chip requires a corresponding driving system. In this work, the driving method we adopt is passive matrix (PM). In order to connect the driving system with the display chip, we designed and fabricated a special printed circuit board (PCB). By fixing the chip on the PCB and then connecting to the pad on PCB with aluminum wire, the chip can be connected. Figure 3a demonstrates the block diagram of the driving system applied in this work. The control core of the system is a field programmable gate array (FPGA). Input the signal from the personal computer (PC) to the FPGA, as shown by the experimental setup in figure 3b, the image signal is processed by the FPGA, passed to the LED driver, and then connected to the 64 pins of the Micro-LED chip to realize the display driving. Here, we demonstrate a graphics display using our Micro-LED display chip. The image of "NJU" was displayed on the blue Micro-LED chip, shown in figure 3c, corresponding to the designed pattern. As can be seen from the image, some of the pixels are not working properly. Most device failures were due to incomplete etching of thick SiO_2, resulting in weak connection. This issue can be solved by optimizing the etching parameters. Figure 3d demonstrates the transparent images of the Micro-LED display chip working under daylight. Through the transparent display chip, the famous scenery building of Nanjing University can be seen clearly in distance. Of course, much work need be done to give higher yield and performance. Nevertheless, the results in this work proved the great potential of GaN-based transparent Micro-LED chip for display applications.

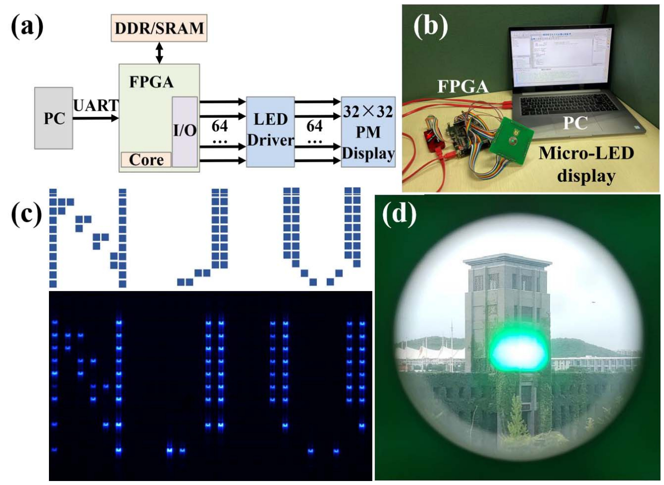

Fig. 3. (a) Block diagram of the driving system. (b) Experimental setup of the device connection. (c) Designed "NJU" pattern, and the displayed "NJU" image on Micro-LED chip. (d) Transparent images of Micro-LED display.

IV. Conclusion

In summary, GaN-based transparent Micro-LED display chip based on double-side polished sapphire substrates was designed and fabricated with a single pixel size of 20 μm×20 μm, and a resolution of 254 PPI. Its reverse leakage current is less than 1 nA (@-1.5 V). Its transparency reaches 80% among the whole display area by the optimized design of pixel array, including transparent ITO electrodes, non-patterned sapphire substrate, wide pixel space and narrow metal wires. The brightness of the pixels reaches up to 25000 nits, and the emission peaks of blue and green pixels show red shift of about 2 nm and 4 nm with operation temperatures from 20 °C to 110 °C, respectively. Graphics images were demonstrated using our Micro-LED display system. Experimental results in this letter provide solid evidence to satisfy the demands of display applications. The technique might broad application prospects in augmented reality, smart glasses, and etc., and these results have exhibited the promising potential strategy for the development of transparent display.

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