High Performance GaN-based Micro-LEDs with Improved Ambient Contrast Ratio

Ke Zhang[1,2], **Tingting Han**[3], **Hoi-Sing Kwok**[1,2], **and Zhaojun Liu***[1,2]

[1] State Key Laboratory of Advanced Displays and Optoelectronics Technologies, the Hong Kong University of Science and Technology
[2] Department of Electrical and Electronic Engineering, Southern University of Science and Technology
[3] Shenzhen Refond Optoelectronics CO., LTD
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ABSTRACT

GaN-based Micro-LEDs have shown great potential in various filed, such as solid-state lighting, display, sensor, visible light communication and multifunctional devices. The performance of Micro-LEDs in various operating environment drew enormous attention recently. We report high performance Micro-LEDs on sapphire substrate with device size scaling to 30um and ultra-high current density of 100A/cm2 under applied bias of 4V. The Micro-LED devices can keep comparable performance after extreme environment test with an emission wavelength of 460nm. We also proposed three method to improve ambient contrast ratio including optical method, anti-reflection film and optimized device structure.

1 INTRODUCTION

Recently, micro-LEDs has received a great deal of research interest due to their superior properties such as self-emission, high brightness and efficiency, low power consumption, long lifetime, and wide operating environment [1-3]. It has been widely used as solid state lighting because of the great energy saving properties. In the decades-long development of LED, it has become Irreplaceable lighting source and backlight with efficiency more than 200 lm/W. Besides, more and more research about LED solar cell were also reported with good FF (fill factor) and photoelectric conversion efficiency. Besides, micro-LED was also used to for temperature sensor, light detector for some high integrated and multi-functional devices [4]. Micro-LED display gained considerable attention in recent years, Prof. Z. J. Liu's team reported 360 PPI Backlight-unit-free (BLU-free) micro-LED projector by optical synthesis in 2012 and 1700 PPI micro-LED display in 2014 Compound Semiconductor Integrated Circuit Symposium [5]. In 2018, Jade Bird Display reported a 5000PPI micro-display with low power consumption and also showed a VR demo in the Society for Information Display Week [6]. Furthermore, higher modulation bandwidth, shorter device carrier lifetime and smaller device capacitance enables micro-LED higher modulation speed to support visible light communication (VLC), which has been reported in 2016, supporting 1.25-Mb/s for a bit error rate $<10^{-5}$ up to $>$500cm distance with a lens [7]. Besides, micro-LEDs are very small, taking up 1% area in display, which shows great potential for fully integrated multi-function devices.

2 EXPERIMENT

The GaN Micro-LED was implemented on a single sapphire substrate using LED fabrication process. The fabrication process of the Micro-LED array includes 5 photography steps which are MESA structure (MS), current spreading layer (SL), p and n electrode layer (EL), passivation (PS) and contact pads for flip-chip bonding. The pattern on the mask is the same for steps of passivation and contact pads, so the same mask was used but the former step is for wet etching and the later step is for the lift-off. The cross section including material and thickness of each layer is shown in Fig. 1. Micro-LED devices with different pixel size were fabricated as shown in Fig. 2.

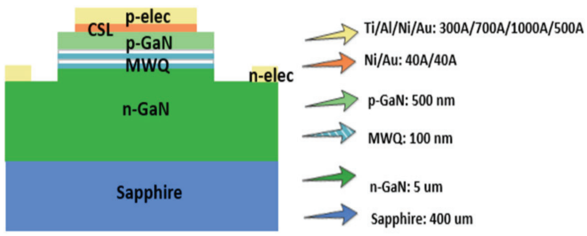


Fig. 1 Cross section and detailed information of the Micro-LED devices

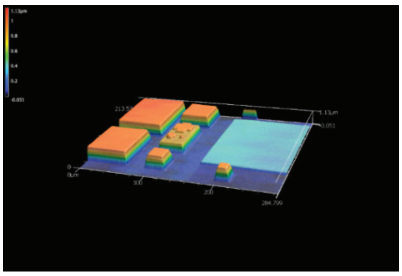
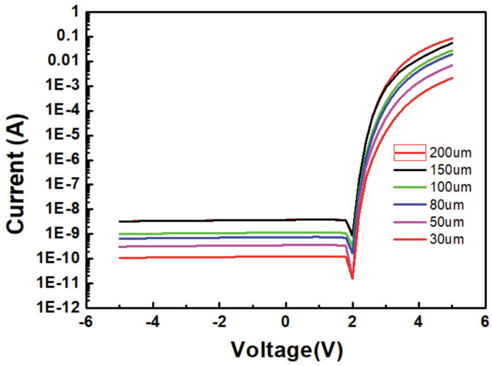
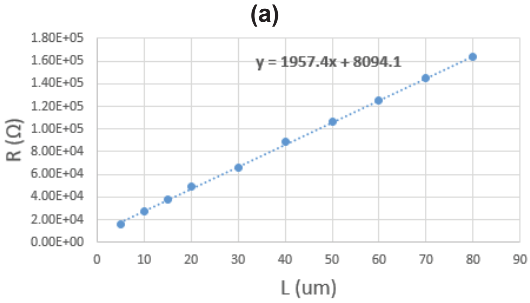


Fig. 2 Three-dimensional photo of the Micro-LED devices with different sizes

The I_V Characteristics of micro-LED with varied size has been measured as shown Fig. 3 in both linear and log scale. These devices have great electrical performance, forward voltage can be as small as 2.9 V and leakage current can be 1E-10 A. At the same applied voltage, larger size pixel has larger current, which is reasonable according to the p-n junction electrical equation. However, smaller pixel has larger current density which was supposed to be the same for different size pixels. That means, smaller pixel has better electrical efficiency which may be caused by lower current crowding phenomenon. TLM (Transmission line measurement) were measured for both p-GaN and n-GaN. The contact resistance for p and n are about 4047 Ohm and 2.6 Ohm respectively.



(a)



(b)

Fig. 3 (a) I_V characteristics of Micro-LED devices and (b) TLM measurement of p-GaN

3 RESULTS

ACR (ambient contrast ratio) was used to evaluate a display's performance in the presence of ambient light which is defined as Eq. 1. ACR has already been widely used to evaluate the sunlight readability of transflective LCDs. Recently, this concept is also extended to OLED and mini/micro-LED displays. For Micro-LED devices, light will be emitted through the sapphire to the environment directly and can be also reflected by the metal electrode to the environment which will increase the brightness. However, this metal electrode will also reflect ambient light and reduce ACR eventually. To improve ACR, three methods were proposed. The first one is to use optical devices such as polarizer and QWP (quarter wave plate), which is adopted for OLED display before. Using an anti-reflection coating film is another method, which may effectively improve the ACR with the sacrifice of brightness. And the third one is to change the micro-LED device itself to get optimized structure design.

$$ACR = \frac{L_{on}+L_{ambient}\times R_L}{L_{off}+L_{ambient}\times R_L} \quad (1)$$

For the optical method, 2 polarizers and 1 QWP were used. A linear x polarization light will be turned to a right circular polarization light through polarizer and quarter wave plate. After reflecting, it will be changed to a left circular polarization light and go through quarter wave plate again. Finally, a linear y polarization light was achieved, which will be stocked by the original polarizer. A linear x polarization light will be turned to a right circular polarization light through polarizer and quarter wave plate. After reflecting, it will be changed to a left circular polarization light and go through quarter wave plate again. Finally, a linear y polarization light was achieved, which will be stocked by the polarizer.

The second method is to coat an antireflection film which will reduce the reflection phenomenon. As shown in Fig. 4, it is clear that when the display is under the offstate, the panel without coating shows more obvious light reflection than the panel with coating. Since L_{off} is almost 0, the total ACR will be reduced when reflection increase according to Eq. 1. In this way, the ACR of the panel can be improved, however the anti-reflection coating will also block the light emitted from the device to some extent, sacrificing some brightness.

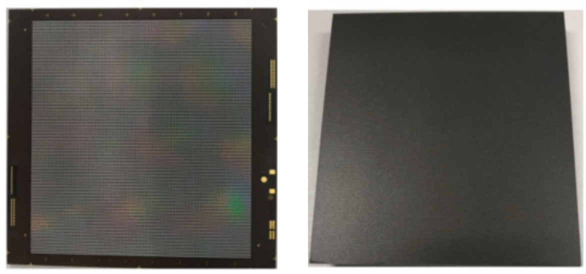


Fig. 4 Comparison of Mini-LED display without and with anti-reflection coating

The third method is to optimize the micro-LED device itself. To investigate the relationship between the electrode area and the reflection ratio, we used 4 kinds of Micro-LED display arrays with pixel pitch of 60, 30, 15, and 10 um respectively. With the same PCR (Pixel Covered Ratio), those 4 arrays showed different light reflection as shown in Fig. 5, indicating that higher ECR (Electrode Covered Ratio) ratio leads to stronger reflection. The detailed information the 4 arrays including PCR, ECR and pixel pitch were shown in table 1. Besides, 3 kinds of samples were compared here including blue epitaxy sample, green epitaxy sample and bule epitaxy sample with PSS (Patterned Sapphire Substrate) substrate. The blue one certainly have higher reflection ratio under the short wavelength light. For the sample with PSS substrate, which means sapphire was patterned firstly and grown epitaxy then, the reflection ratio showed quite low among each array with different pixel pitch compared with other samples.

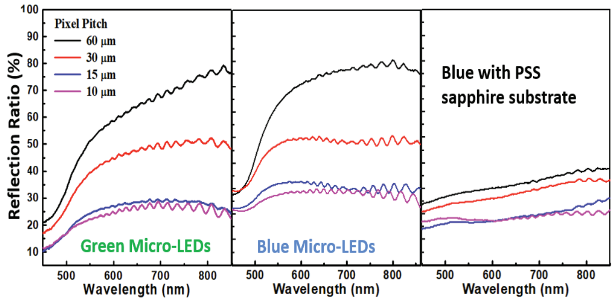


Fig. 5 Reflection ratio comparison of Micro-LED arrays with different pixel pitch

Table 1 Detailed design parameters of Micro-LED arrays with different pixel pitch

Array	Array 1	Array 2	Array 3	Array 4
Pitch	60 um	30 um	15 um	10 um
PCR	64%	64%	64%	64%
ECR	6%	46%	4%	25%

Pixel size has obvious influence of ACR can be also proved by comprising mini-LED and micro-LED as shown in Fig. 6. The pixel pitch of the Mini-LED display and the Micro-LED display are 700 um and 30 um respectively. The reflection phenomenon of Mini-LEDs is significantly lower than Micro-LEDs, indicating the reduction of metal electrode area will increase the ACR, however will reduce the electrical efficiency. Since Micro-LEDs have significant advantages of high brightness of micro-LEDs, some brightness can be sacrificed to improve ACR in this case.

The on state and off state radiation of the panels were tested. Three kinds of light source were used, including blue, white and yellow. Take white light as an example, it's clear in the Fig.7, the ACR of Mini LED is 9.1 times of micro-LEDs. And with the coating, the brightness of RGB mini-LEDs will reduced by 3.9 times, while the ACR still increased by 2.5 times. It's necessary to note that this figure is based on white light. Although the effect of optical method and coating method is similar in this figure, the ACR of optical method should be higher if better broad band optical device were used.

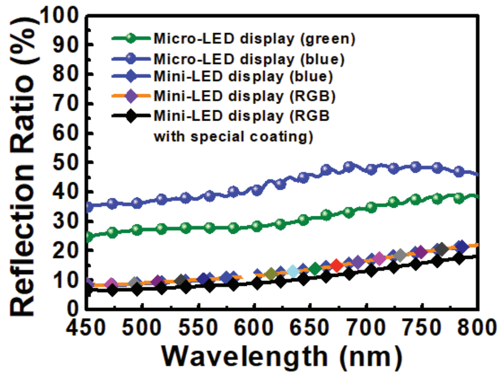
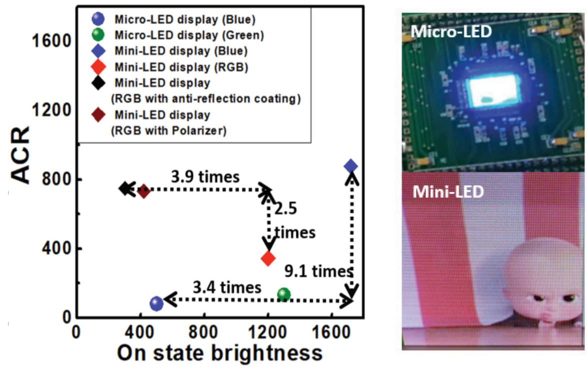


Fig. 6 Reflection ratio comparison of Micro-LEDs with different pixel pitch



(a) (b)

Fig. 7 (a) ACR comparison between Micro-LED display and mini-LED displays with different improved method (b) part of demos for Micro-LED and Mini-LED display

In summary, optical method and antireflection coating can improve the ACR while sacrificed the brightness. More optical devices and coating material should be tried to get the optimized design. Device structure optimization is very useful to improve the ACR, which can be used with the previous two method at the same time. More pixel structure with different PCR and ECR will be designed to trade off between the electrical efficiency and light reflection ratio. Different electrode material including ITO will be investigated to reduce light reflection and remain the electrical performance at the same time.

4 CONCLUSIONS

High quality micro-LED devices with V_f of 2.9V were fabricated. The detailed fabrication process and material were introduced. Devices with different size were also fabricated to investigate the relationship between the electrical performance and pixel size. Three method were proposed to improve the ACR. The optical method and coating method can improve the ACR of about 2.5 times while sacrificed the brightness. The ACR can be also improved by optimized the device structure which may affect the electrical efficiency, so a trade-off should be done in the future.

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