REVIEWS

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Characteristics and techniques of GaN-based micro-LEDs for application in next-generation display

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Abstract: Due to the excellent optoelectronic properties, fast response time, outstanding power efficiency and high stability, micro-LED plays an increasingly important role in the new generation of display technology compared with LCD and OLED display. This paper mainly introduces the preparation methods of the GaN-based micro-LED array, the optoelectronic characteristics, and several key technologies to achieve full-color display, such as transfer printing, color conversion by quantum dot and local strain engineering.

Key words: micro-LED; GaN; full-color display; transfer printing; color conversion

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1. Introduction

From plasma display panel (PDP), cathode ray tube (CRT) to liquid crystal display (LCD), and then to organic light-emitting diode (OLED) and quantum dot light-emitting diode (QLED), the competition for the new generation of display technology has never stopped the pace. As the OLED and QLED challenge the LCD and dominate the whole display market, micro-LED has entered the field of vision because of its excellent properties of high brightness, great color gamut, fast response time, outstanding power efficiency, high stability and so on[1–5]. Micro-LED display has promising applications ranging from wearable devices such as wristbands and watches to commercial billboards, public displays, and the virtual reality (VR) or augmented reality (AR) devices[6–9].

As shown in Table 1, micro-LED has advantages of excellent image quality, superior stability and other outstanding factors compared with LCD and OLED[1, 2, 10–12]. Firstly, compared with LCD, self-emissive micro-LED could decrease the device thickness because of the absence of color filters and backlight units. In addition, the brightness and contrast ratio of micro-LED is as high as 100 000 cd/m^2 and ∞, respectively. Also the PPI of micro-LED display can be more than 1500 and reaching 10 000[13, 14]. The response time of micro-LED is very short reaching 0.2 ns, ~ 10^4 times shorter than that of OLED. The lifetime of micro-LED is estimated by the Arrhenius formula indicating that the lifetime is more than 10 years, more competitive compared with LCD and OLED. Secondly, there are a wide view angle (~178°) and high color gamut (> 100%, NTSC) belonging to micro-LED[10, 15, 16]. Due to such excellent properties, micro-LED is regarded as the promising light source in future display direction.

Sony, Apple, Samsung and many academic researchers regard micro-LED as the next-generation display, and continue to increase the research investment. However, there still exist several challenges of micro-LED display technology, such as massive transfer and full-color display of micro-LEDs. At present, the full-color display of micro-LED can be achieved by transfer printing red, green and blue (RGB) micro-LED, exciting quantum dots (QDs) to achieve full color, and designing RGB micro-LED pixels on the same wafer through local strain engineering and growth[19–21]. Here, we will introduce the basic preparation methods of the micro-LED array, the optoelectronic characteristics, the modulation bandwidth and the typical techniques to achieve full-color display.

2. The basic micro-LED processing techniques

For micro-LED processing, the metal-organic chemical vapor deposition (MOCVD) is used to perform the epitaxial layer growth on the substrate. For example, the epitaxial GaN wafers grown on silicon substrate are introduced, and then chip fabrication process is carried out. The reason of making use of silicon as substrate here is that it has the advantages of large size, low cost, high thermal conductivity and can be integrated with Si based microelectronic devices. Also the silicon substrate has more advantages in the growth of high-efficiency LED with long emission wavelength, such as red, green and yellow[22]. A cleaned silicon is served as a substrate in MOCVD and the corresponding precursor gas is injected to grow the epitaxial LED layers. As shown in Fig. 1(a), it can be seen that the epitaxial layers mainly include a GaN buffer layer, an n-doped GaN layer, an InGaN/GaN multiple quantum well (MQW) layer, a current block layer of AlGaN, and a p-doped GaN layer. Then, a current spreading layer of indium tin oxide (ITO) was evaporated on top of the wafer. Then, the chip fabrication will be adopted to process the epi wafer, as shown in Fig. 1(b). ITO current spreading layer and epitaxial layer are patterned and etched to n-GaN layer by self-alignment, forming micro-LED mesa array. Then the SiO_2 is deposited through plasma enhanced chemical vapor deposition (PECVD) as passivation layer and at last Ti/Au is depos-

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Table 1. The comparison of main characteristics of micro-LED, LCD, and OLED.

Parameter	LCD	OLED	micro-LED
Emission type	Backlight/LED (thick)	Self-emissive (thin)	Self-emissive (thin)
Brightness (cd/m²)	3000	5000	100 000[1]
Luminescent material	Inorganic	Organic	Inorganic
Contrast ratio	5000 : 1	∞	∞[1]
PPI	>300	1500–6000[12]	1500–10 000[14, 17]
Color gamut	75%, NTSC	>100%, NTSC	>100%, NTSC[1]
Viewing angle	Best (~178°)[18]	Best (~178°)	Best (~178°)[1]
Response time	5 ms, slow	10 μs, medium	0.2 ns, fast[1]
Lifetime	Medium	Medium	Long[1]
Operating temperature	233–373 K	238–358 K	15–500 K[1, 12, 15]

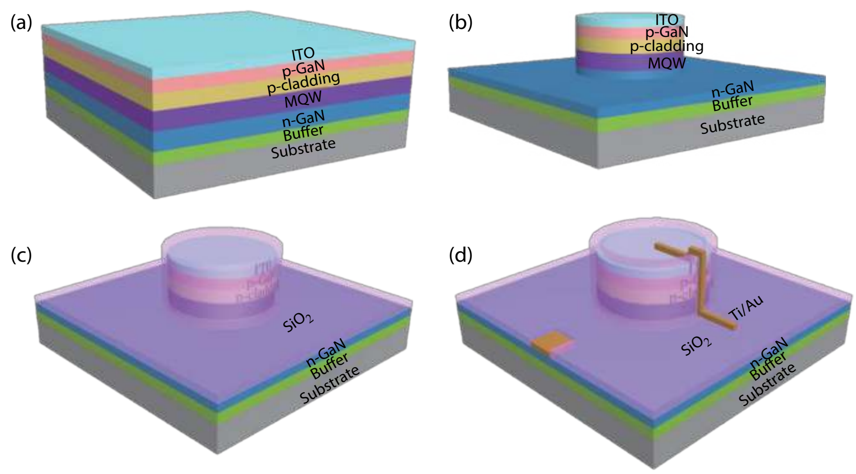

Fig. 1. (Color online) (a) The GaN-based epitaxial structure with silicon substrate. (b) Etching to n-GaN layer to form a micro-LED mesa array. (c) The deposition of SiO_2 through PECVD. (d) The deposition of Ti/Au to serve as electrodes.

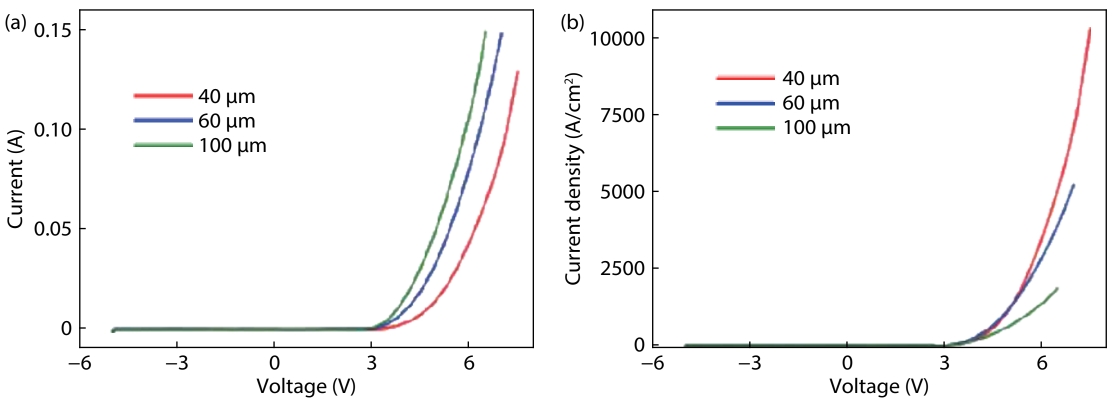

Fig. 2. (Color online) (a) *I–V* curves of blue micro-LED pixels with different sizes. (b) The curve of current density for blue micro-LED with different sizes.

ited to serve as electrodes as shown in Figs. 1(c)–1(d).

3. The performances of micro-LED

Herein, many performance tests have been carried out to verify the excellent characteristics of micro-LED. The *I–V* characteristics of micro-LED are similar to those of p–n junction diode in classical semiconductor theory. From the *I–V* curves of blue micro-LED pixels with different diameters prepared on the same epitaxial wafer, series resistance of the pixels increase with the decrease of chip size, as shown in Fig. 2(a)[23, 24]. The variation is mainly caused by the reduction of micro-LED size. Fig. 2(b) shows the curve of current density of blue micro-LED versus the bias voltage. The current crowding effect of small pixel is smaller and the current distribution is more uniform under the same bias voltage, so the current density of small pixel at the same voltage is higher.

Optical properties are one of the fundamental and important properties of micro-LEDs, so other tests such as *L–I* also have been carried out. As shown in Fig. 3(a), it can be seen from the curve that the maximum output power increases with the increase of pixel size at the same current. And the curve of the corresponding light-output power versus current density is shown in Fig. 3(b). The smaller size of micro-LED devices, the higher maximum optical power density that

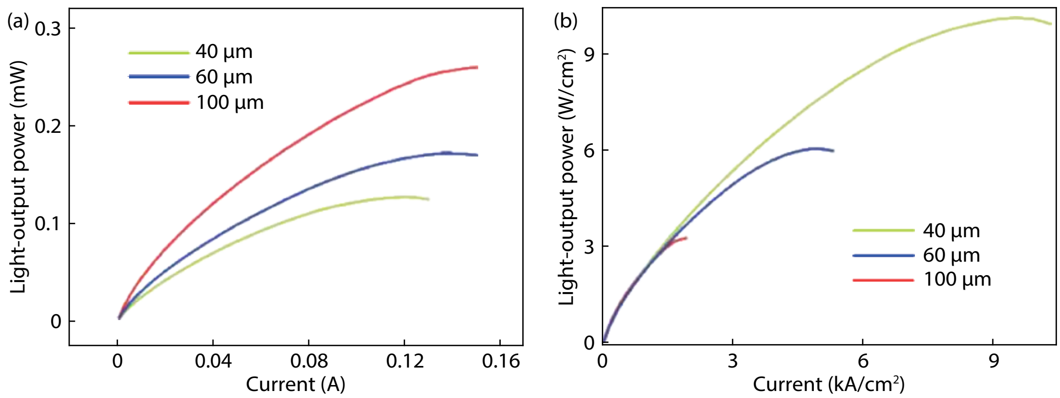

Fig. 3. (Color online) (a) *L*–*I* curves of blue micro-LEDs with different diameters. (b) The curve of the light-output power density versus injection current density for blue micro-LED with different sizes.

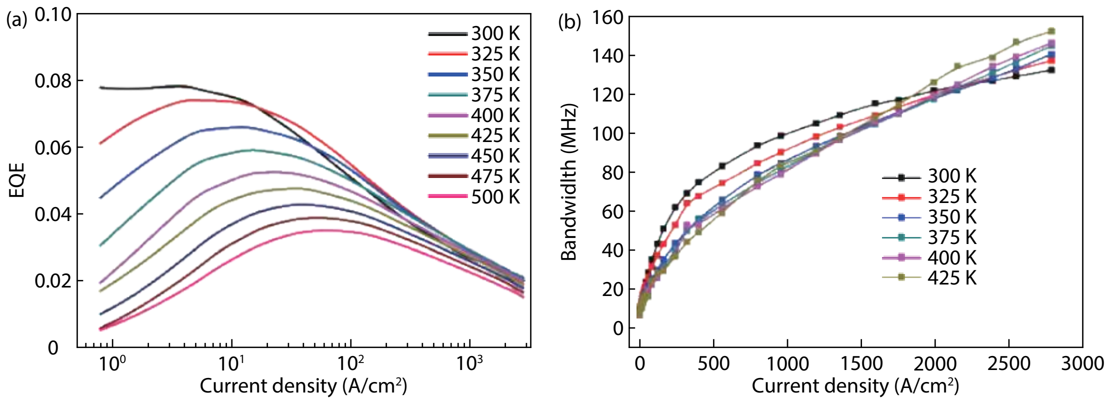

Fig. 4. (Color online) (a) EQE versus current density from 300 to 500 K with 25 K temperature increment on a semi-logarithmic scale. (b) Bandwidth versus current from 300 to 425 K to show the trend with temperature[25]. Copyright 2014, Applied Physics Letters.

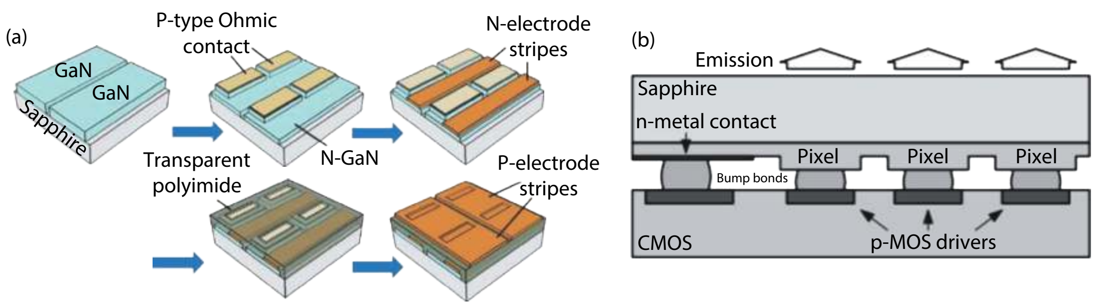

Fig. 5. (Color online) (a) The schematic of passive matrix micro-LED array[16]. (b) The schematic of active matrix micro-LED array[28]. Copyright 2015, IEEE Transactions on Electron Devices.

can be output, and the smaller micro-LED devices can sustain higher injection current density according to the Fig. 2. The results also indicate that micro-LED has the advantages of high saturation current density and high light-output power density. Based on these performance tests, the brightness of micro-LED display can be up to 100 000 cd/m^2[1]. Therefore the high luminance of micro-LED can easily satisfy the requirements for AR and other high-performance display applications.

After the corresponding electrical and optical properties were tested, the external quantum efficiency (EQE) and bandwidth were also analyzed[25, 26]. And the results indicated that the operating temperature of micro-LED can reach 500 K. Fig. 4(a) also shows the characteristic curve between EQE and current density on a semi-logarithmic scale with the device temperature varying from 300 to 500 K in 25 K increments. It can be seen that with the increase of temperature under the same current density, the EQE peak decreases a lot and the peak of EQE shifts to the high current density. At low current density, less than 10 A/cm^2, the EQEs drop obviously with increasing temperature. The curve of bandwidth versus current density at different temperature is shown in Fig. 4(b), and it can be seen that the bandwidth shows different trend at different current densities. As the temperature increases from 300 to 425 K, the bandwidth decreases when the current density is below 2000 A/cm^2. With the current density above 2500 A/cm^2, the bandwidth increases with the increasing temperature.

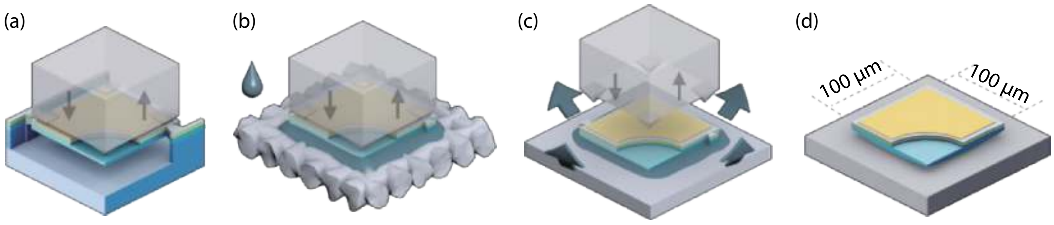

Fig. 6. (Color online) Schematic of transfer printing using capillary bonding. (a) Using an elastomeric stamp for the pick-up of a suspended micro-LED. (b) Upon pick-up, micro-LED is compressed against an acetone-wetted cloth. (c) Released micro-LED when the backside contacts receiving substrate. (d) After thermal curing, the micro-LED is bonded to the new substrate[19]. Copyright 2015, Optics Express.

4. The key micro-LED technology in full color display

The driving modes of micro-LED are divided into passive matrix and active matrix[27, 28]. As shown in Fig. 5(a), during the dry etching of GaN down to the sapphire substrate and standard photo-lithography, the individual pixels are defined and a group of horizontal and vertical pixels share the same electrode to form a matrix structure respectively. Fig. 5(b) shows an active matrix structure, and we can see that the cathode of the pixel is connected through sharing n-GaN layer. In addition, the anode of all pixels is bonded with the Si-based CMOS driving backplate to form an individually addressable micro-LED array.

Also for the full-color display scheme, because of the continuous research of colorization and high brightness, many full-color display techniques have been developed, including RGB tricolor LED method by transfer printing red, green and blue micro-LEDs, UV or blue LED exciting color converters, and RGB micro-LED pixel through local strain engineering.

As shown in Fig. 6, the transfer printing scheme will be introduced. Capillary bonding is achieved by introducing an intermediate step to the transfer printing process, in which the substrate of the micro-LED being transferred is underetched by KOH solution[19]. After pick-up from the donor wafer, the backside is wetted on an acetone impregnated standard clean-room wipe as shown in Figs. 6(a)–6(b). Quick retraction of the stamp removes the micro-LED die from the wipe with its backside still wet, and it is then deposited onto the receiver substrate. After thermal curing, the micro-LED is bonded to the new substrate as shown in Figs. 6(c)–6(d).

At present, the massive transfer of micro-LED is still a bottleneck. The main technical challenges include the requirement of very high stability and accuracy of the transfer process. For RGB full-color display, as only single-color high-efficiency micro-LED can be developed on the same substrate, it is necessary to transfer the RGB micro-LEDs separately from different substrates, which requires very accurate technology to transfer a large amount of micro-LEDs that results in increasing difficulty of the transfer process.

Due to the high efficiency characteristics, the RGB technique may be the mainstream technique in the future[29, 30]. However, due to the different power efficiency and driving voltage of micro-LEDs with different colors, chromatic aberration may occur. Other full-color display schemes have been proposed for research which may alleviate such problems.

Here color conversion technique has also been researched, which mainly uses UV micro-LED to stimulate red, green and blue luminescent medium such as phosphor or QDs to produce light of specific wavelength, and then full-color display can be achieved through matching the tricolor[31, 32]. Due to the progress of QD technology, the particle size of QD is generally 1–10 nm, which can be applied to the micro-LED with smaller size, and the luminescence color is determined by the material and would be affected by the particle size. However, QD technology still has some drawbacks, such as poor stability, short life and packaging. At present, the technology of spin-coating and mist spraying has been used to develop hybrid micro-LED/QD device. The atomizer and airflow spray out uniform QDs with controllable size, to coat QDs on UV/blue LED to achieve full color display[19]. As shown in Fig. 7(a), standard MQW LED epitaxial layers are grown on sapphire substrates and etched to form UV micro-LED arrays. In Figs. 7(b)–7(d), the aerosol jet printing method is used to spray the RGB QDs on the micro LED array. The QDs solution is aerosolized and entrained in a gas stream in this way. Therefore, the operation of spray is precisely controlled by the computer system, and the quantity of the QDs can be monitored in real time. In addition, Kuo *et al.* have performed another research to reduce the optical cross-talk effect through a simple lithography method. Photoresist is used to fabricate the mold, which consists of a window for QDs jetting and a blocking wall for optical cross-talk reduction[33]. Finally, in Fig. 7(e), a distributed Bragg reflector (DBR) is added to the top of micro LED arrays to reduce the leakage of UV light in the display application. There are still several disadvantages, for example, the phosphors or QDs may have low conversion efficiency as they are coated on the surface of micro-LED pixel.

Growth methods, such as strain engineering method after the growth of epitaxial layer and chip fabrication, also have been designed to achieve full color on the same wafer[21]. The RGB subpixels are fabricated as schematically shown in Fig. 8. The blue and green colors are generated by local relaxation of the strain in the MQWs through using nanopillar structures, while the red color is generated by the membrane structure itself. Here the color is controllable by varying the nanopillar diameter of the MQWs. In this study, 150-nm diameter and 50-nm diameter nanopillars for the green emission and blue emission have been fabricated, respectively. And the fabrication process of the full-color LED pixel consisted of three major steps, including the fabrication of nanopillar structures by photolithography and etching, planarization and electrical insulation treatment, and finally the patterning of electrical interconnects, as shown in Figs. 8(a)–8(c). Also, there still exist several problems need to be solved, such as the optimization of epitaxial growth of a longer ($\lambda \sim$ 650 nm) wavelength micro-LED structure, the fabrication pro-

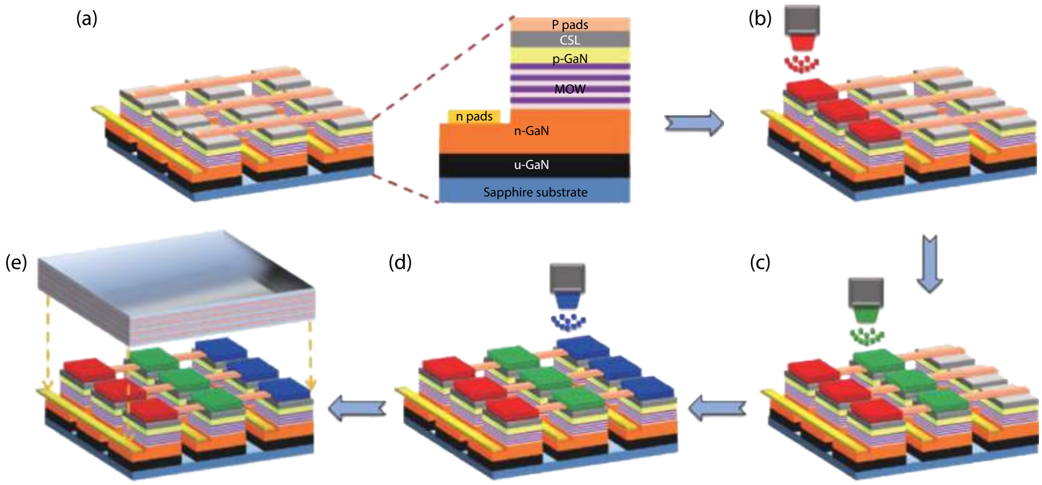

Fig. 7. (Color online) (a) Standard MQW LED was grown on sapphire substrates for the micro-LED arrays. (b) The using of aerosol jet printing method to spray the red QDs on the micro-LED array. (c) The spraying of green QDs on the micro-LED array. (d) The spraying of blue QDs on the micro-LED array. (e) The DBR was added to the top of micro LED arrays[20]. Copyright 2015, Optic Express.

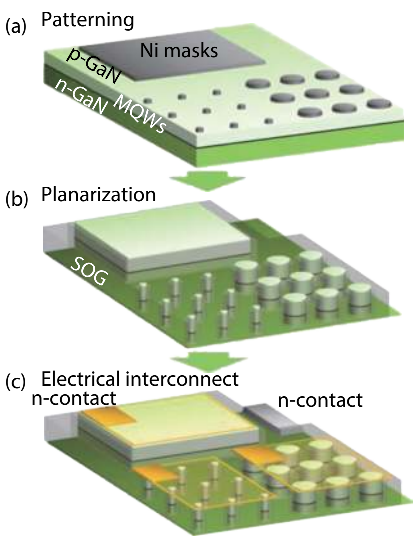

Fig. 8. (Color online) Schematic of the fabrication process for the RGB LED pixel. (a) The fabrication of nanopillar structures by photolithography and etching. (b) Planarization and electrical insulation treatment. (c) Formation of electrical interconnect[21]. Copyright 2017, Applied Physics Letters.

cesses to yield better electrical properties for small-diameter nanopillar micro-LED, and an improvement of the subpixel areas and so on.

There are also many other full-color display schemes, such as optical lens synthesis. The RGB micro-LED arrays were packaged on three packaging boards respectively and connected with a control board and a trichromatic prism, and then the brightness of the trichromatic micro-LED is adjusted to achieve colorization[34]. At present, it is most likely to achieve a large-scale full-color display, mainly based on transfer printing and UV/blue micro-LED color conversion. Several related displays have been demonstrated[35, 36]. Although there still exist some technical problems to be solved, with the continuous research, these obstacles will be solved in the near future.

5. Conclusion

This review paper has described the basic characteristics and techniques of micro-LED for next-generation full-color display, mainly including the preparation process, the characteristics compared with LCD and OLED display, the related electrical performance and optical performance, and the full color techniques. With the development of micro-LED, it is expected that micro-LED will play an important role in academia and industry in the future display.

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