Study of Quantum-Dots based Color Conversion Technology for Full-color Micro-LED Displays

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Abstract

Micro-LED is considered to be an important display technology based on the third generation semiconductor, which has been focused on by many research groups and enterprises nowadays. It is a display technology that takes self-emitting micron scale LED as luminous pixel unit and assembles it on the driving panel to form high-density LED array. Micro-LED is different from LCD and OLED, as an inorganic self-luminescent device, it has greater advantages in brightness, resolution, contrast, energy consumption, service life, response speed and thermal stability. Based on people's higher requirements for display brightness, resolution and response speed, full-color micro-LED display technology has been the focus of development. Among full-color micro-LED display methods, color conversion technology based on quantum dots has high research potential. This report will review the development of color conversion technology.

Author Keywords

Micro-LED, full-color display, micro-display, quantum dot, ink-jet printing, photoresist, nanostructure.

1. Introduction

Recently, micro-LED (micro light-emitting diodes) display has become the most promising display technology[1]. Micro-LED is a micron-scale self-luminous pixel array device based on wide band gap semiconductor--GaN material with high efficiency and stability, its structure and array arrangement are shown in Figure 1. The size of each micro-LED can be lower than about 100 μm which means that it can provide higher resolution. This advantage allows micro-LEDs to be used as self-emissive display rather than being backlights in LCD[2][3]. Compared with traditional LCD (Liquid Crystal Display) and OLED (Organic Light-Emitting Diode) display, micro-LED has obvious advantages in luminescence performance, which are shown in Table 1. However, the smaller size also means more challenges like difficulty in mass transfer and the problem of wavelength consistency, which lead to its higher price.

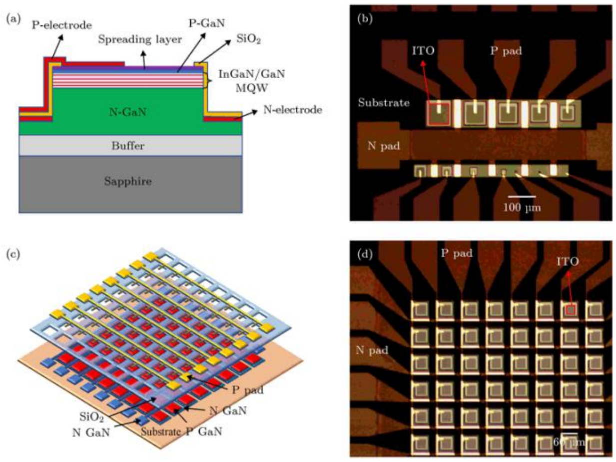

Fig. 1. (a) the diagram of the micro-LED structure. (b) (c) (d)the image of the micro-LED array.

Table 1. The excellent performance of Micro-LED compared to other display technologies

Technology	LCD	OLED	Micro-LED
Mechanism	Backlighting	Self-emissive	Self-emissive
Response Time	ms	μs	ns
Luminance	3000cd/m^2 (full color)	1500cd/m^2 (full color)	~10^5 cd/m^2 (full color)
Working Temperature	0 to 60℃	-50 to 70℃	-100 to 120℃
Life Time	long	short	long
Cost	low	high	high

As a self-emissive display technology, full-color display of micro-LED is one of significant research directions. To achieve full-color micro-LED display, there are sevral solutions like RGB micro-LED full-color display and color conversion full-color display[1]. RGB micro-LED full-color display is currently the common approach for large LED screens[1][4], but this method is based on the mass-transfer process, which remains challenging because of its low transfer yield, slow throughput, and high fabrication cost[5][6]. Color conversion based on quantum dots (QDs), which requires blue or UV LEDs as a lighting source, has been suggested as a way to reduce the difficulty of the mass-transfer process[7][8].Quantum dots are nanoparticles composed of elements in groups II-VI or III-V , which have the effects of electroluminescence and photoluminescence, and can emit fluorescence after being excited. The luminescence color is determined by the material and size, so the different wavelength of luminescence can be changed by adjusting the particle size of quantum dots. QD is suitable for being applied with smaller size micro-LED display, which can achieve high contrast ratio[7]. This study reviews the color conversion technology based on QDs, including inkjet printing, photolithography, and nanostructures.

2. ink-jet printing technology

Various fabrication methods of quantum dot layers have been developed, among which inkjet printing has become the most effective fabrication method due to its advantages of high accuracy, free mask , material saving, simple and fast manufacturing, and low cost. Inkjet printing technology was first applied in 2015. Han et al.[7] applied aerosol jet printing technology to spray RGB QDs on the surface of UV micro-LED array to achieve full color μ-LED display, which is shown in Figure 2. The size of the UV micro-LED chip was 35 μm ×35 μm which spaced 40 μm apart. They used a sprayer and airflow control to spray the dots uniformly and in a controllable size. The schematic diagram of device and principle is shown in Figure 3. They used 365 nm uv light to excite quantum dots of different sizes, the emmison peak wavelengths of 450 nm, 520 nm, and 630 nm corresponding to the partical size of 2.47 nm, 6.17 nm and 9.29 nm, respectively.This research laid the foundation for the subsequent development of quantum dot technology for full-color micro-LED display.

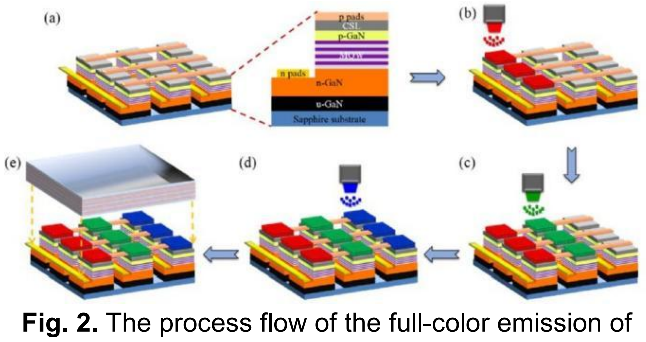

Fig. 2. The process flow of the full-color emission of quantum-dot-based micro LED display.

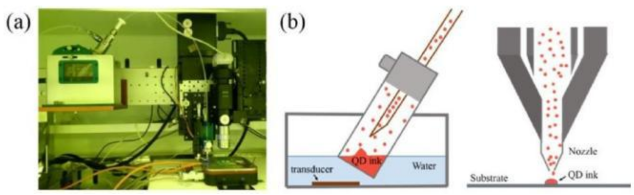

Fig. 3. (a) The image of aerosol jet printing. (b) The schematic pictures of aerosol jet printing.

One of the technical challenges of micro-LED color conversion is how to remove the residual blue excitation light from LEDs. One solution is placing a distributed Bragg reflector (DBR) structure on top of QD layers to avoid emission of blue light[9]. Another method is to place a color filter, which consists of three main colors: red, green and blue[10]. However, both of these methods need to be added during the manufacturing process, resulting in higher cost. Cost effective and simpler technologies are needed to evolve. The easiest way is that QDs themselves can absorb blue light because of their high absorbtion ability for the light wavelength below 450nm. Osinski and Palomaki found that CdSe/CdS and perovskite materials have more than 99% blue light absorption capacity in the 5 μm layer with 20-30% volume fraction, while InP/ZnSe/ZnS may not be able to do so when each shell thickness is more than one or two layers. This is because the transparent or weekly absorption shell rapidly increases the volume fraction of the QDs required for a given absorption.[11]. To solve this problem, Lee et al. [12] found that InP/ZnS QD film absorbs more than 95% of blue light with the thickness of about 10 μm. All these studies show that QD films have great potential for high absorption applications. In order to completely eliminate residual blue light and obtain better QDS film, the concentration and film thickness of QDS can be further optimized in the future.

3. QDPR structure(QDs combined with photoresist)

Another way to mass produce high-resolution micro-LED displays and overcome the technical difficulties of mass transfer is the photolithography process[13][14]. After surface modification, QDs can be combined with photoresist (PR) to form QDPR[13]. The precision image of QDPR is shown in Figure 4. QDPR provides a way to control the size and thickness of multicolor QD arrays while preserving the advantages of photolithography. This method provides a solution to achieve high-resolution and large-scale QD pattern, which is applicable to not only display, but also to practical photonic device research and development.

One of the problems that inkjet printing failed to address in Han's study was optical crosstalk between QDs, which is about 32.8 %. This resulted in blurred boundaries between adjacent pixels. To solve this problem, in 2017, Lin et al.[15] inserted a photoresist mold between the pixels, which consists of a window for QD injection and a barrier wall for reducing crosstalk, as shown in Figure 5. Their experimental results showed that this QD structure combined with the photoresist mold significantly reduced the value of optical crosstalk to near zero. The appearance of QDPR structure provides a new direction for the optimization of QD design, and also provides technical support for the application of QD in microLED display.

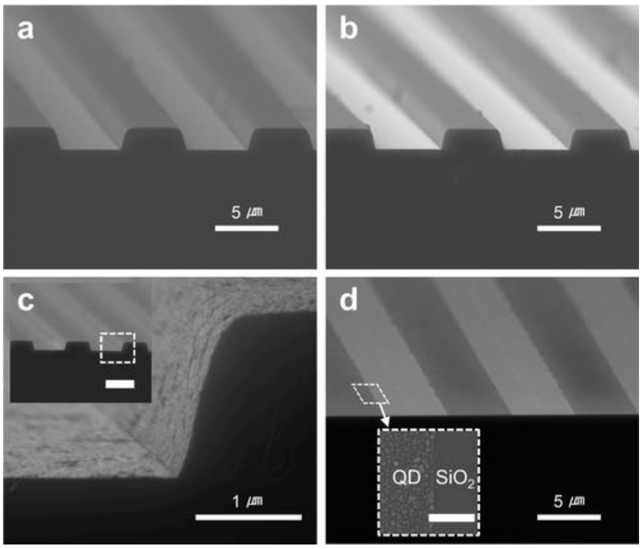

Fig. 4. SEM image of QDPR on SiO2 substrate.

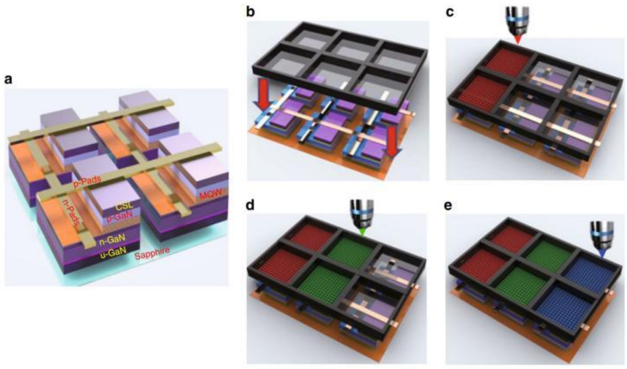

Fig. 5. Process flow of QD structure combined with the photoresist.

4. Nanohole, nanorod, and nanoring structures

In order to reduce the gap between QDs and multiple quantum wells(MQW), Krishnan et al.[16] demonstrated a photonic quasicrystal hybrid LED geometry, as shown in Figure 6. They etched periodic nanopores on the surface of LED chips and deposited quantum dots in the nanopores, so that the QDs can be directly in contact with MQWs.

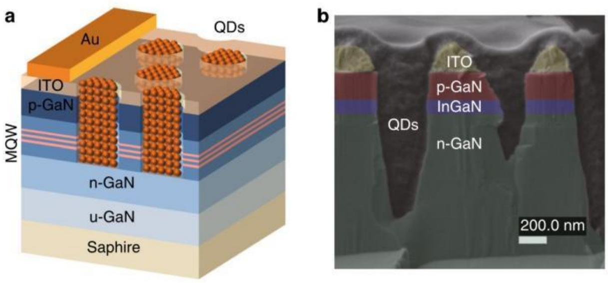

Fig. 6. The image of nanohole structure

Before explaining how this structure improves color conversion efficiency, the concept of a mechanism need to be known first, which is called the nonradiative Förster resonant energy transfer (FRET) mechanism[17]. The basic idea is to generate more light from the QD by transferring excess excitons from MQW to the quantum dot acceptor. There are an important condition must be met for FRET which is the transfer path between donor and acceptor excitons should be sufficiently small (typically <10 nm)[18]. Therefore, to meet this condition, the gap between MQW and QD needs to be as short as possible.

This structure led to a record effective quantum yield(QY) of 123% for single-color conversion LEDs and 110% for white light-emitting devices[16]. An excellent hybrid III-nitride/nanocrystal nanohole LED has been developed by Zhuang et al.[19], which have been demonstrated with a high color rendering index, up to 82, covering the white light emission at different correlated color temperatures ranging from 2629 to 6636 K.

In addition to the nanopore structure, Liu et al.[20] deposited QDs on nanorod-shaped MQWs, which showed a 32.4% improvement in color conversion efficiency compared to traditional LEDs. Unlike the nanopore or nanorods structures, only the inner or outer sidewall can contact QDs, a novel nanoring structure that both the inner and outer sidewalls contact QDs has also been proposed to improve FRET effect in 2017[21], the structure is shown in Figure 7. The results show that reducing the wall width of the nanoring LEDs can effectively suppress the quantum confined Stark effect(QCSE) and change the emission wavelength of the nanoring LED. Chen et al.[22] fabricated a full-color hybrid QD-NR micro-LED display based on this structure, which is shown in Figure 8. This display enables the color gamut overlap of the National Television System Committee (NTSC) space achieve about 104.8% and that of Rec. 2020 is 78.2%, which is supportable enough for full-color display in practical applications.

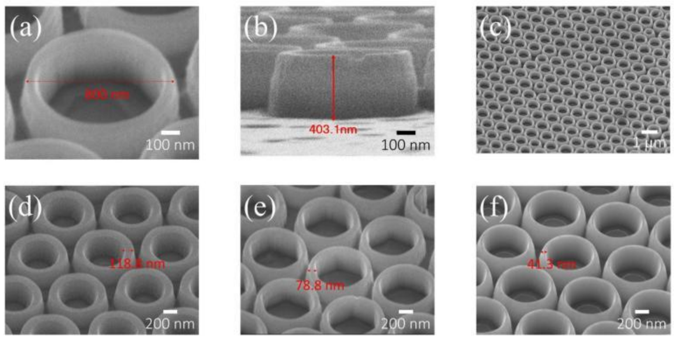

Fig. 7. SEM image of nanoring structure.

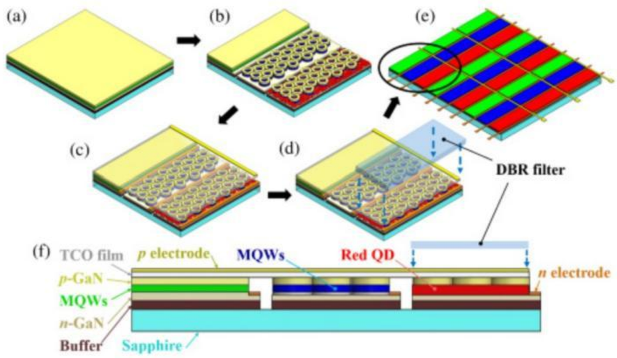

Fig. 8. Process flow of QD-NR micro-LED display.

5. Conclusion

For full-color solutions of micro-LED display, the traditional RGB color conversion chip has the problems of insufficient brightness and low composition ratio when the size of LED chip is less than 20 μm[23], The development of QD technology is expected to solve this problem. Inkjet printing technology pioneered the application of QDs in full-color display of micro-LED. With the research on quantum dot materials, the problem of residual blue excitation light in LED has been gradually solved. QDPR structure solves the optical crosstalk problem left by inkjet printing, and provides a foundation for the innovation of quantum dot structure. The combination of QDs and nanostructures provides a new idea for the development of QD structures, which greatly improves the effective quantum yield of QDs and provides a wider color gamut. No matter from inkjet printing to photolithography, or the emergence of nanostructures, quantum dot technology is promoting the wider application of microLED full-color display. However, the main problem of the above technology is the uniformity of colors and the interaction between colors, so solving the separation of red, green and blue colors and uniformity of colors has become one of the important problems for the application of QD LED in microdisplay. In addition, the current QD technology is not mature enough, there are also poor material stability, high requirements for heat dissipation, and the need for sealing, short life and other shortcomings. This has greatly limited its applications, but as the technology advances and matures, we expect QDs to have the opportunity to play a more important role.

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