Photolithographic Quantum-Dot OLED Display

Rongzhen Cui*, Huanhuan Zhang*, Teng Pan, Yadi Liu**, Shaokun Hou**, Junwei Liu**, Dan Wang**, Lijuan Wang**, Wangfeng Xi*, Rubo Xing*, Xiujian Zhu***

*Visionox Technology Inc., Kunshan, Jiangsu, China

**Yungu (Gu'an) Technology Co., Ltd.(Gu'an Visionox), Hebei, China

Abstract

In this paper, full-color photolithographic QOE (QD on encapsulation) display with 326 PPI was realized. QOE shows merits of wide viewing angle, high color gamut and free of fine metal mask. Compared with QD-OLED with adhesive process, QD on encapsulation (QOE) with low post baking temperature has been demonstrated to be more superior in cost, efficiency and accuracy. It is noteworthy that photo conversion efficiency (PCE) and DCI-P3 color gamut of QOE are over 40% and 120%, respectively.

Author Keywords

Quantum dot; QD-OLED; photolithography; viewing angle; color gamut; accuracy; photo conversion efficiency.

1. Introduction

Over the past decades, organic light-emitting diodes (OLEDs) have emerged as one of the most attractive organic optoelectronic technologies due to their inherent merits of self-emitting feature, flexibility and low power consumption [1]. However, application of OLED in some certain market remains a challenge to some degree. The quantum dot (QD) is another core materials of display [2,3]. QD color conversion (QDCC), absorbing blue light and emitting red or green light, has been applied to displays [4,5]. The novel technology of QD-OLED, dynamic integration of QDCC and blue OLED (BOLED), is consider to be promising because of high color gamut, wide viewing angle and high contrast ratio.

Fine metal mask (FMM) is needless for QD-OLED and WOLED. The advantage of these two methods is solving all issues related to FMM, including evaporation process and mask fabrication. In contrast with WOLED, QD-OLED displays higher efficiency and color gamut.

Variety of methods, such as inkjet printing, photolithography and transfer printing, are employed for the fabrication of QDCC[6,7]. Inkjet printing might be applied to large size displays. Photolithography is the attractive candidate for the demand of high resolution in displays.

Herein, photolithographic QD-OLED with different structures were revealed. In addition, BOLED, QDCC and pattern were also discussed. Finally, full-color photolithographic QD-OLED display with 326 PPI was realized.

2. Results and Discussion

2.1 Structures and methods

Figure 1 described the device structures of photolithographic QD-OLED with adhesive process and photolithographic QOE. As shown in Figure 1(a), based on glass substrate, black matrix and color filter were patterned with photolithography to block the unabsorbed blue emission. The pattern of bank and QDPR were realized with similar process, resulting in color conversion. Post baking temperature of all QDCC materials were above 140℃. Eventually photolithographic QD-OLED was obtained by attaching QDCC substrate to the blue OLED substrate. This indicated increasing the cost and restricting the application to some degree. In this case, structure of QD on encapsulation (QOE) directly was promising. Detailed flow was as follows. Based on thin film encapsulation (TFE), bank and QD patterns were achieved by means of photolithography. Low post baking temperature was essential to prevent the damage of blue OLED.

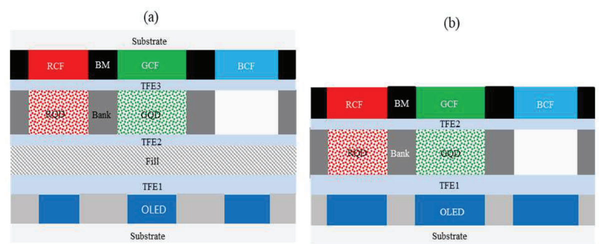

Figure 1. Structures of QD-OLED with adhesive process (a) and QOE (b).

QDPR sample was prepared with the method of spin coating on glass or OLED substrate. The patterned sample was encapsulated utilizing thin transparent film. The photo conversion efficiency (PCE) and photo absorption efficiency (PAE) of QD-OLED was defined and evaluated in Figure 2.

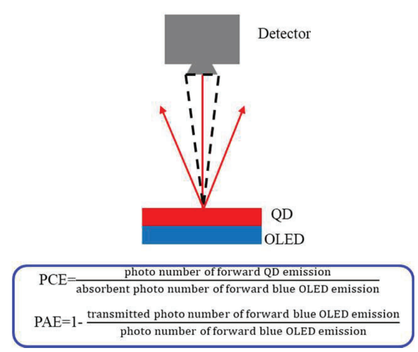

Figure 2. Schematic diagram of measurement and formulae of PCE and PAE.

2.2 Blue OLED

In terms of QD-OLED, blue OLED with more superior performances, such as higher brightness and longer lifetime, was essential. Tandem device structure was demonstrated feasibility of achieving desired parameters mentioned above. Compared with single OLED, tandem OLED displayed lower current density at the same brightness, ascribed to higher current efficiency. Therefore, long lifetime was realized for tandem

ISSN 0097-996X/25/5601-0538-$1.00 © 2025

OLED. Efficient three-stack tandem blue OLED was developed by optimizing micro-cavity structure and doping concentration. Three-stack tandem device structure and electroluminescent spectra were shown in Figure 3. The blue index and lifetime of tandem device increased to more than 2.2 and 5.2 times, respectively. The efficient tandem BOLED provided feasible backlight for the application of QD-OLED.

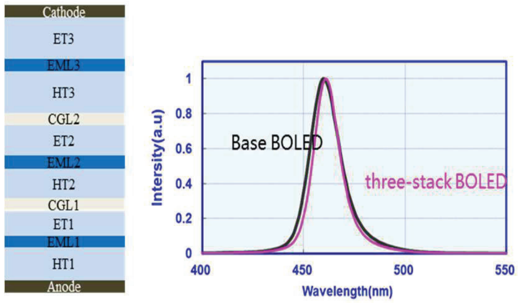

Figure 3. Three-stack tandem device structure and electroluminescent spectra.

2.3 Optimization of QD color conversion

To ensure PCE and pattern, many details need to be considered, such as matching of QD and photoresist, dispersion and concentrations of each component, diameter distribution of scattering particle, and so on. Besides concentrations of QD and scattering particle in QDPR, the thickness also played crucial role in improving PCE. Regrettably, PCE of QD-OLED with adhesive process was less than 20%.

PCE of QOE was evaluated subsequently, due to the high cost and low efficiency of QD-OLED with adhesive process. Besides concentrations of QD and scattering particle in QDPR, the thickness also played crucial role in improving PCE. As depicted in Table 1, PCE of QD increased firstly and then decreased with increasing thickness of R QDPR gradually. QDPR achieved the maximum PCE above 40%. Experimental results revealed that PCE was reduced by higher or lower thickness because of serious self-absorption, decreased optical path length and absorption of blue light. PAE of RQD was higher than that of GQD. In addition, all PAE were above 95%. Experimental results demonstrated QOE is promising.

Table 1. Optical properties of QDPR in QOE

	PAE	PCE	Wavelength
RQD	＞95%	＞40%	630±3um
GQD	＞95%	＞40%	530±3um

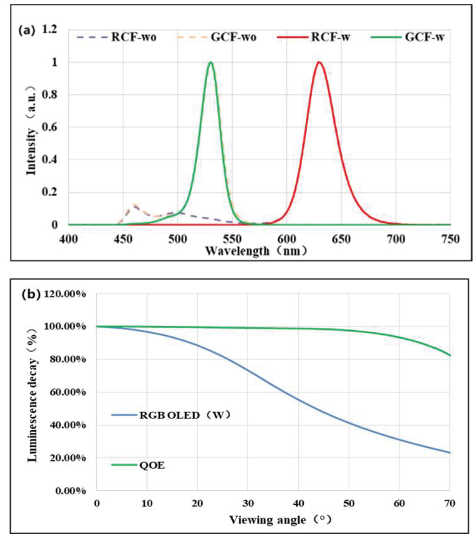

Figure 4. (a) Normalized spectra of QOE with and without CF. (b) normalized luminance decay with different viewing angle

Color purity and viewing angle were subsequently evaluated. As described in Figure 4(a), a fraction of leaked backlight was observed, although QDPR showed high PCE. To ensure color purity, CF structure was added and optimized. Finally, pure red and green spectra were observed, peaked at 630 nm and 530 nm, respectively. The DCI-P3 color gamut of QOE without CF was only 80%, owing to leaked blue emissive through QDPR. However, QOE with CF showed high DCI-P3 color gamut of 128%. Details were in Table 2. Figure 4(b) exhibited luminance decay with different viewing angle. QOE showed slower luminance decay than that of OLED, which is attributed to the effect of micro-cavity. Eventually, QOE achieved luminance decay of below 10% even at wide viewing angle of 60°.

Table 2. Wavelength and color gamut of QOE

	Wavelength	DCI-P3 (without CF)	DCI-P3 (with CF)
QOE	460/530/630	80%	128%

2.4 QDPR patterning and QOE display demo

For QOE, QDPR film was prepared with spin coating, following pre-baking temperature of 85℃ for 3min. Then, it was exposed within the dose of 50-100mj utilizing 365 nm UV light. Patten was obtained by using KOH developer, following post baking at 85℃ for 60min. In addition, QDPR realized resolution of 10 um. Detailed process flow of photolithographic QOE and images were shown in Figures 5 and 6. Finally, 326PPI display demo based on photolithographic QOE was achieved.

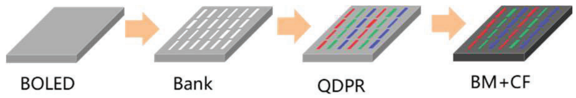

Figure 5. Process flow diagram of photolithographic QOE.

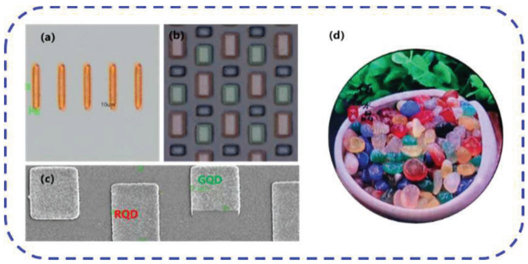

Figure 6. Images of resolution (a), pixels (b), SEM (c) and 326PPI QOE display demo

3. Summary

In conclusion, full-color photolithographic QD-OLED display with 326 PPI was achieved. Compared with QD-OLED with adhesive process, QOE with low post baking temperature has been demonstrated to be more superior in cost, efficiency and accuracy. Therefore, it is crucial to further develop the materials and structure of QOE. We believe that photolithographic QOE with high color gamut, wide viewing angle and high contrast ratio is promising in the next generation display.

4. References

1. Zhang D, Duan L, Li C, Li Y, Li H, Zhang D, et al. High-Efficiency Fluorescent Organic Light-Emitting Devices Using Sensitizing Hosts with a Small Singlet–Triplet Exchange Energy. Advanced Materials, 2014, 26: 5050-5055.
2. Dai X, Zhang Z, Jin Y, Niu Y, Cao H, Liang X, et al. Solution-processed, high-performance light-emitting diodes based on quantum dots. Nature, 2014, 515: 96-99.
3. Chen O, Zhao J, Chauhan V, Cui J, Wong C, Harris D, Wei H, et al. Compact high-quality CdSe-CdS core-shell nanocrystals with narrow emission linewidths and suppressed blinking. Nature Materials, 2013, 12: 445-451.
4. Osinski J, Palomaki P. Quantum dot design criteria for color conversion in microLED displays. SID Symposium Digest of Technical Papers, 2019, 50: 34-37.
5. Sakai N, Wenger B. Red Perovskite Emitters for Color Conversion and LEDs. SID Symposium Digest of Technical Papers, 2021, 52: 892-894.
6. Lee E, Kan S, Hotz C, Yurek J, Luo Z, Yamanaga J, et al. SID Symposium Digest of Technical Papers, 2017, 44: 984-987.
7. Kim T, Cho K, Lee E, Lee S, Chae J, Kim J, et al. Full-colour quantum dot displays fabricated by transfer printing. Nature Photonics, 2011, 5: 176-182.