High-performance Micro-cavity white-OLED Technology for 1,500ppi real RGB Glass-based VR Display

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Abstract

To achieve wide-color-gamut and high-efficiency micro-displays, 2-stack B/RG and 3-stack primary R/B/G white-OLEDs are fabricated, respectively. The former incorporating micro-cavity technology shows up to 33.8 cd/A higher equivalent white efficiency @ D65, > 98% wider color gamut coverage of DCI-P3, and high color consistence irrespective of process deviation, even at high current density. This work enables 1,500ppi real RGB glass-based VR's evolution from monochrome to high-performance full-color displays.

Author Keywords

Tandem OLED, Glass-based VR, Color Gamut, Micro-cavity.

1. Introduction

Along with the increasing expectation for more immersive interactive experiences, wearable VR and AR have gradually integrated into human life. Corresponding, the demands for light weight, high resolution, low power consumption and wide color gamut are more urgent. Among various technologies, OLED on Si wafer (OLEDoS), which Apple Vision Pro adopts, is capable of generating high quality images that meet most of the technical requirements of VR scenarios, except for the high cost.

In general, two different manufacturing methods of full-color micro-OLED displays have been adopted, including ①the direct patterning RGB-OLED [1] by SNM (Silicon Nitride Mask) or FMM (Fine Metal Mask), and ②color-filter-based white-OLED [2-4] by open mask. The former has advantages of high luminance and wide color gamut, as well as disadvantages of the complicated and immature process restricting its commercial application in super-high-resolution technology. Conversely, the efficiency and color gamut remain the great challenge in mature color-filter-based technologies.

Apart from the luminance loss caused by color filters, the theoretical maximum optical efficiency of compact polarized-based catadioptric lens structures, also known as folded pancake lens, is merely 25%. Moreover, the low persistence of emitting time per frame is required to reduce the motion blur effect. These unique requirements lead to a 100x increasing demand for luminance of micro-display, e.g., 100 nit luminance into eyesight require about 10,000 nit luminance from displays.

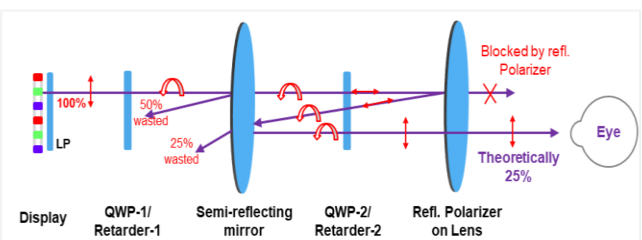

Figure 1. Pancake Structure Diagram adopted in commercial VR optical system. [5]

Based on the above analysis, the improvement of color-filter-based white-OLEDs has been researched and considered as a potential technology to satisfy the requirement of low-cost commercial VR products.

During the 2025 display week, the monochrome super-high-ppi glass-based VR display have been demonstrated, which emphasized the TFT backplane structure. In this paper, the technical paradigm is centered on realization and improvement of full color displays integrated color-filter-based white-OLED technology.

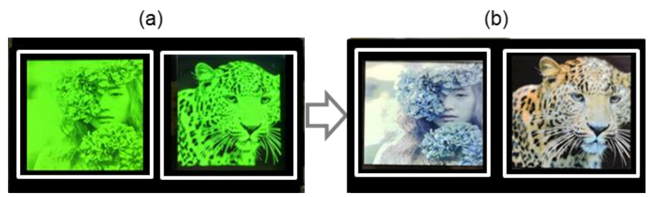

Figure 2. 1,500ppi 1.43inch real RGB glass-based display iteration from (a) monochrome, to (b) full-color.

A comparative analysis of tandem white-OLED devices will be presented in the following sectors. Multiple influential factors such as OLED devices, thin film encapsulation and color filters, process variations are investigated to address the challenges of resolution, efficiency and color gamut.

2. White-OLED Structure Design

Tandem white-OLED design can effectively increase the luminance and maintain the reliability, however, the increased thickness of unpatterned stacked-OLED layers aggravate the current leakage, resulting in low current efficiency and poor color gamut in high-ppi displays. Furthermore, the raised forward voltage across stacked-OLED brings about new problems, such as high-voltage driving IC requirement.

The micro-cavity technology [3, 6] realized by the patterned transparent-ITO or HIL/HTL (hole injection/ transport layer), helps to reduce the thickness of unpatterned common layers and improve the whole performance.

This section seeks to provide a comparison between the strong-micro-cavity B/RG (2-stack) and primary R/G/B (3-stack) white-OLEDs. The former refers to an optical micro-cavity modulated by photolithography process, e.g., transparent ITO; the latter refers to a separated red, green, and blue EML (Emitting Material Layer) connected by two CGLs (Charge Generation Layer), respectively.

(a) *Micro-cavity design to improve efficiency and suppress lateral current leakage*

In conventional color-filter-based white-OLED structures, all organic materials are evaporated by open mask, contributing to the high-resolution micro-OLED displays. As shown in Figure 3-(a), a long optical resonant distance (abbr.as d_opt.) between

CPL (Capping Layer) and reflective electrode is designed to achieve a relative equilibrium of red/green/blue efficiency.

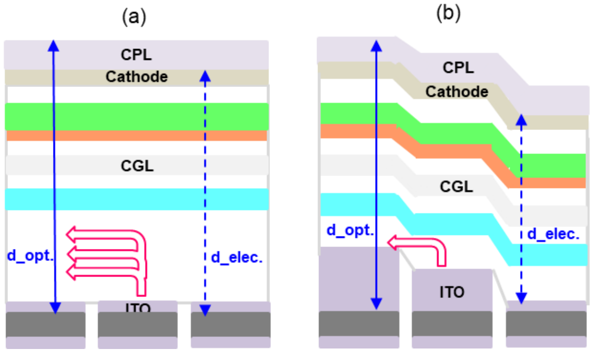

Figure 3. Structural iterative design of 2-stack tandem white-OLED, (a) conventional moderate micro-cavity device, (b) strong micro-cavity (MC) modulated by supplemental-ITO layer.

Meanwhile, long optical distance (d_opt.) brings about long electric distance (abbr. as d_elec.), which triggers a serious lateral current leakage and degrades color gamut in high-resolution micro-displays. Thereby, various undercut structures and low-conductive materials are introduced to suppress the lateral current leakage. At all events, the reduction of overall distance, namely thinner OLED thickness, benefits the voltage and current leakage.

To address the limitations of the high-precision and low-efficiency, the lithographic supplemental-ITO film is introduced to serve as the optical modulation layers (Figure 3-(b)). It not only fulfill the optimal optical performance of individual red/green/blue colors, but also suppress the electric crosstalk aggravated by the increased thickness of stacked-OLEDs. Higher luminance and wider color gamut would be predictable.

(b) Micro-cavity modulation layer (ITO) fabricated by photolithography process

Based on the above analysis, additional steps of lithography and sacrificial-layer deposition process are developed to fabricate different thickness of the micro-cavity modulation layers. Sacrificial-layers such as metal oxide are introduced to improve the temperature-related spontaneous-crystallization, induced-crystallization and subsequent-etching characteristics of the supplemental-ITO film. (Figure 4)

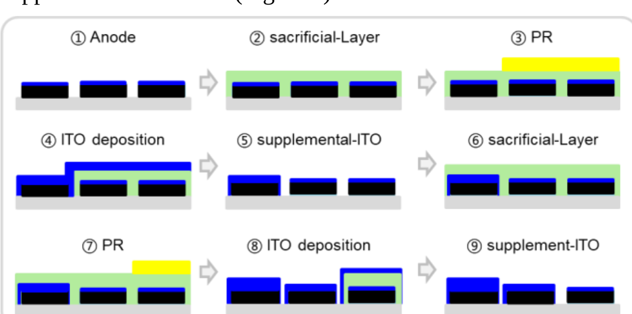

Figure 4. Process flow of cavity modulation layer ITO fabricated by photolithography process.

Three different thicknesses of ITO films in Anode are illustrated in Figure 5. The relative experimental differences of 30 nm and 80 nm are basically consistent with the design requirement of optical cavity length.

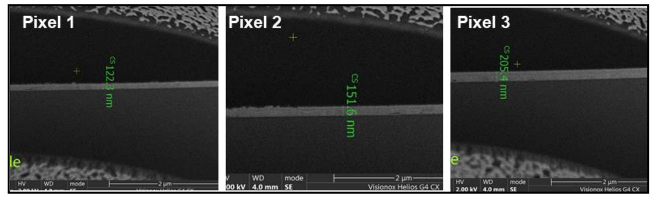

Figure 5. FIB diagrams of different optical modulation layer (ITO) thickness fabricated by lithography process.

Then, micro-cavity white-OLEDs (MC-OLED) modulated by supplemental-ITOs are fabricated and compared with the conventional white-OLED device.

As shown in Figure 6, the dashed line and solid line symbols represent conventional white-OLED (WOLED) and micro-cavity OLEDs (MC-x), respectively. A markedly increased intensity and higher color purity have been achieved, even for the devices without color filters (MC-x in 6-(a)).

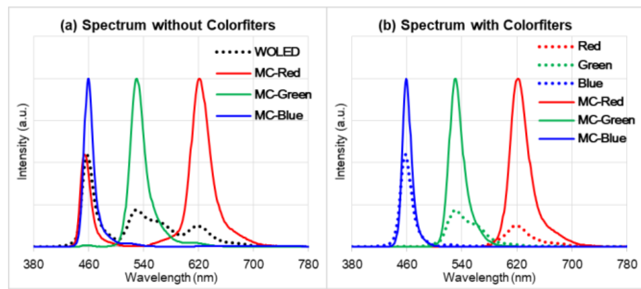

Figure 6. Spectrums of 2-stack white-OLED devices, (a) without color filters, (b) with color filters.

(c) Primary R/G/B OLED design to improve the trade-off between Red and Green color

Alternatively, 3-stack primary-R/G/B white-OLED device (7-a) is designed to optimize the electric and optical performance for individual color. Benefit from the separated R/G/B emitting-units design, higher current efficiency and wider color gamut can be achieved.

Figure 7 depict the structure and the improvement. Compared with 2-stack B/RG device, the red & green efficiency of primary-R/B/G 3-stack device have increased respectively by 80% and 40%, accompanied by 21% blue index decline. Synchronous pixel arrangement adjustment enables this new structure design to be conductive to the extremely high-performance realization of VR products.

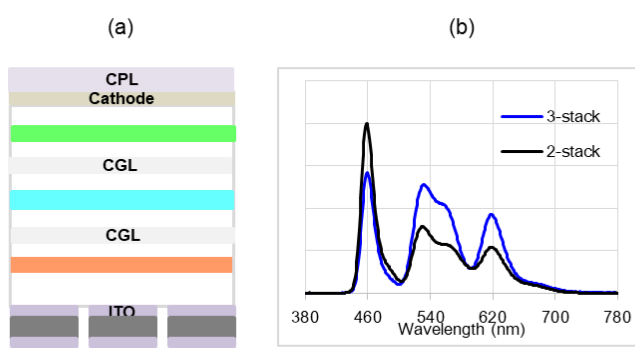

Figure 7. (a) Structure of primary R/G/B 3-stack white-OLED, (b) Spectrums of 3-stack R/G/B vs. 2-stack B/RG.

(d) Performance compared among these devices

Detailed performance of the above designed devices are compared in the following part, such as color gamut, voltage, efficiency combined with the same color filters at 55 mA/cm^2.

The comparative data at high current density are listed in the Table 1. The equivalent white efficiency increases twice from 13.1 cd/A (2-stack B/RG), 15.6 cd/A (3-stack primary-R/B/G) to 33.8 cd/A (optimum 2-stack MC-WOLED), mainly from the efficiency improvement of red and green color. The impressive characteristic guarantees the low power consumption and high reliability demand for VR application.

Table 1. Characteristics of 2-stack and 3-stack white-OLED devices with color filters @55 mA/cm^2

Parameters		2-stack		3-stack
		B/RG	MC-WOLED	primary-R/B/G
		3-a	3-b	7-a
Voltage (V)		7.5	7.4	10.3
White Eff. (cd/A) @D65		13.1	33.8	15.6
Color Gamut	DCI-P3	83.4%	98.5%	89.2%
	BT.2020	60.3%	81.7%	65.0%
C.E. (cd/A)	Red	6.9	29.2	9.7
	CIE	(0.653, 0.336)	(0.667, 0.331)	(0.663, 0.330)
	Green	28.3	72.9	52.7
	CIE	(0.311, 0.649)	(0.220, 0.745)	(0.286, 0.681)
	Blue	3.5	4.5	3.9
	CIE	(0.149, 0.057)	(0.147, 0.038)	(0.152, 0.079)

Benefit from the strong micro-cavity technology integration, the color gamut coverage broaden from 83.4% (2-stack B/RG), 89.2% (3-stack R/B/G) to 98.5% (MC-WOLED) coverage of DCI-P3 color gamut.

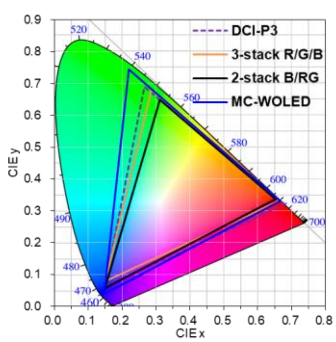

Figure 8. Chromaticity of the designed white-OLEDs.

3. Integrating Optimization

Apart from the OLED design, thin film encapsulation and color filters are optimized to enhance the efficiency and ensure the color consistence.

(a) Optical enhancement by multi-layered index-matching thin film encapsulation

Thinner encapsulation films is beneficial for lower optical crosstalk in high-resolution VR technology. ALD/CVD multi-layered inorganic films are designed to replace the conventional CVD1/IJP/CVD2 encapsulation and optimize the optical resonance, simultaneously.

Figure 9-(a) illustrates the resonance structure between the reflective anode and the designed multi-layered TFEs. Compared with conventional CVD1/IJP/CVD2 encapsulation (BASE), the devices with optimized ALD/CVD multi-layered films (TFE1&2) shows an increased efficiency of red color. This structural design is an improvement solution addressing the efficiency tradeoff between Red and Green colors.

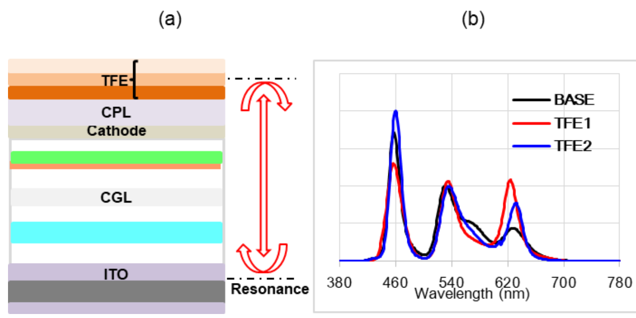

Figure 9. Optical enhancement by different TFEs (a) resonance structure, (b) spectrums of white-OLED with optimized index-matching layers.

(b) Color consistence influenced by process variation of color filters

Two different types of color filters, comprised of high-transmission and wide color gamut materials, are designed to verify the color consistence due to the process deviation. A thickness range of 1.5 um to 2.5 um are combined with the above mentioned devices.

The following Figure 10 illustrate the color gamut deviation with the changes of devices and color filters. No matter how the material and thickness changes, white-OLED devices incorporating the micro-cavity technology (MC-WOLED) show a high color consistence.

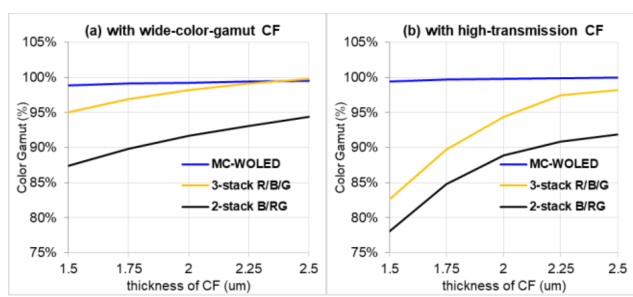

Figure 10. Color gamut deviation combined with the device design and color filter characters, (a) with wide-color-gamut CF, (b) with high-transmission CF.

(c) Color shift optimization

Moreover, the suffering severe color shift with viewing angle is optimized to meet the large-sized glass-based VR requirement.

Taking account of the cavity device, multi-layered TFE and color filters, we successfully alleviate the delta u'v' to < 0.02 @ 60 degree, as for the green, blue, and equivalent white color.

Further optimization of the red color is underway, it is feasible to improve the wide angle deviation and ensure the whole color consistence.

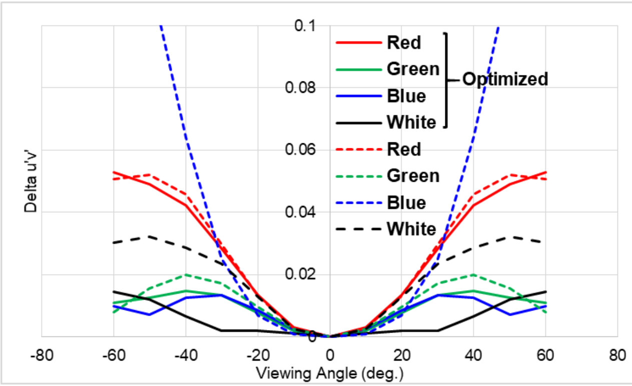

Figure 11. Color shift of the MC-WOLED with color filters before (dashed line) and after (solid line) optimization.

4. Conclusions

This paper demonstrated the super-high-ppi micro-cavity white-OLED technology realized by lithographic supplemental-ITO, providing twice equivalent white efficiency improvement and > 98% wider color gamut coverage of DCI-P3. Additionally, implementing the micro-cavity white-OLED that combine index-matching TFE structure and color filters enables 1,500ppi real RGB glass-based VR's evolution from monochrome to enhanced-performance full-color displays. Meanwhile, other issues such as fringe effect, current leakage and recombination zone exciton-equilibrium are improved. By integrating these optimization approaches, future glass-based micro-OLED displays with enhanced performance could be developed for low-cost commercial VR products.

5. References

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