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A Latest Milestone in WOLED Technology for OLED TV and IT Displays: Enhancing Efficiency, Color Gamut and Longevity

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Abstract

This study introduces a recent innovative progress in white organic light emitting diode (WOLED) technology for premium OLED TV and IT displays. By fabricating a four-stack tandem device consisting of red, first blue, green, and second blue devices in sequence from the anode, we could achieve a current efficiency of the WOLED up to 134 cd/A at 10 mA/cm2, resulting in enhanced efficiency for red, green, and blue subpixels after transmitting color filters. The new OLED TV implementing the four-stack WOLED technology reached luminance levels of 2,900, 1,000, and 400 nit at the average picture level (APL) of 3, 25, and 100%, respectively, and a peak flash luminance of 4,000 nit. Since the four-stack device uses red, green, and blue dopants of saturated color, eliminating yellow green (YG) dopant used for our previous WOLEDs, its color gamut in the Broadcasting service Television (BT)-2020 standard was widen up to 83%. We will explain how to enhance the efficiency and the lifetime in terms of device structure and materials.

Author Keywords

WOLED; 4 stack tandem device; BT2020; OLED TV and IT.

1. Introduction

It has been twelve years since the first large sized OLED TV with a 55" full high definition (FHD) specification was launched in the TV market in 2013.[1] Meanwhile, the size of OLED panels using WOLED and Oxide Thin Film Transistor (TFT) technologies has diversified from 27" to 96", and the resolution has been enhanced to ultra-high definition (UHD) and 8K.[2-4] In terms of application, OLED panels employing WOLED and Oxide TFT technologies have penetrated IT displays such as gaming monitors and specialized monitors. Moreover, WOLED and Oxide TFT technologies realized new product form factors that people had been imagining, such as a rollable TV and transparent TV.[5] Recently, we demonstrated OLED microdisplay for Virtual Reality / Mixed Reality applications, by fabricating WOLED on Si backplane.[6,7]

In the realm of WOLED technology, numerous advancements have been achieved. Initially, as depicted in Fig. 1, a two-stack tandem WOLED was employed, consisting of a fluorescent blue device and a phosphorescent YG device interconnected by a pair of charge generation layer (CGL). The YG dopant exhibited a broad electroluminescent spectrum encompassing both green and red regions and ensured an extended long lifetime suitable for TV displays. Nevertheless, the limited efficiency of the florescent blue device constrained the overall luminance of the panel.

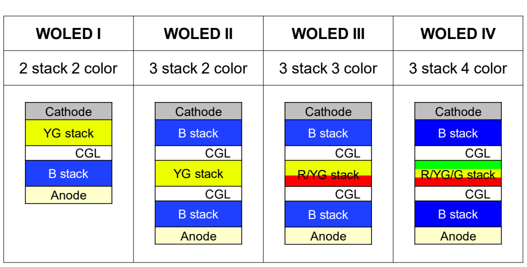

Figure 1. Changes in Device Architectures of WOLED for TV applications. Each stack's EML(s) is sandwiched between HTL and ETL.

By incorporating an additional blue stack, a three-stack tandem WOLED (WOLED II in Fig. 1), where first blue, YG and second blue devices are sequentially stacked, was developed for OLED TV, resulting in 50% increase in luminance.[8] Meanwhile, the new display standard, Digital Cinema Initiative P3(DCI-P3) began to be paid attention to, and there was a growing customers' demand for a wider color gamut. To meet this demand, a red emitting layer (EML) was inserted between the hole transport layer (HTL) and YG EML in the second stack, as illustrated in WOLED III in Fig. 1. With advanced color filters, we could achieve DCI coverage of 99%.[9]

To enhance the luminance of the three-stack tandem WOLED, our innovations were particularly focused on EML materials. When the multi-resonance type thermally activated delayed fluorescent (MR-TADF) blue dopant was first introduced in 2016,[10] we paid attention to its potential due to its photoluminescence spectrum with a narrow full-width half maximum (FWHM). We investigated fluorescent devices employing these boron-nitrogen compounds. These dopants exhibited similar external quantum efficiency to conventional fluorescent blue dopants, but their effective efficiency, considering its color coordinates, was enhanced by 20%. By combining deuterated blue hosts, the narrow FWHM dopant could be applied to OLED TVs named OLED EX.[11] Additionally, by inserting a green EML of high efficiency between the YG EML and electron transport layer (ETL), the EX panel adopted three EMLs of R/YG/G in the second stack, like as WOLED IV in Fig. 1, thereby increasing efficiency and DCI coverage. Through these innovations in fluorescence blue and phosphorescent stacks, the luminance of our OLED EX panel at full window white pattern was increased by 20%.

The emergence of quantum dot (QD)-OLED TV using a competitive technology appeared to pose a threaten to our position in the OLED TV market, because of its high luminance in both primary and secondary colors and its wider color gamut. However, our new OLED panel named Meta which incorporates micro-lens array (MLA) has also demonstrated 25% increase in luminance compared to OLED EX panel.[12] These indicate that WOLED technology-based OLED TVs have been continuously advancing over the past decade.

This presentation will provide a detailed explanation on our latest milestone for OLED TV and IT displays, specifically the four-stack tandem WOLED. The new WOLED has undergone significant changes in its phosphorescent EMLs: the YG EML is no longer used, and the red EML has been separated from the green EML, forming the first stack on the anode. This paper will

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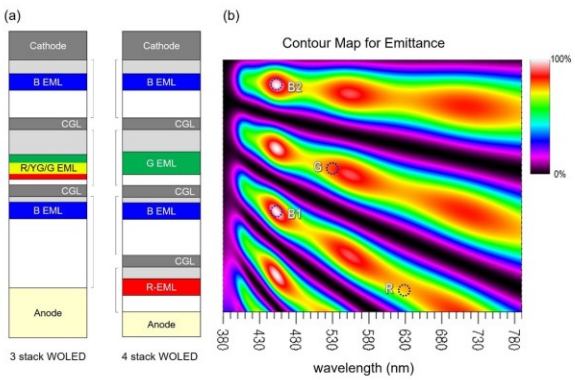

Figure 2. (a) Device Architectures of the latest 3 stack WOLED and 4 stack WOLED (b) Contour map for emittance for 4 stack WOLED. Vertical axis means the location of EML layers.

discuss the performance enhancement of the new WOLED in terms of efficiency, lifetime, and color gamut.

2. Device Architecture

Our four-stack tandem WOLED with bottom emission is fabricated on an indium thin oxide (ITO) anode in the sequence of red, first blue, green, and second blue stacks which are connected with n-CGL and p-CGL without a fine metal mask. As illustrated in Fig. 2(a), when compared with the latest three-stack WOLED (WOLED IV), the total optical lengths, including anode and organic layers, are essentially similar. Except the first stack emitting red light, the positions of EMLs in the four-stack WOLED from the cathode are aligned parallel with the positions of EMLs in the three-stack WOLED.

Figure 2(b) illustrates the contour map of "emittance" for the four-stack WOLED where bottom axis represents the wavelength (nm) of the emitted light and vertical axis represents the position of the light creation within the OLED. The brighter the zone, the higher the emittance value. The emittance is calculated based on the thicknesses and optical constants (n, k) of all layers along the optical path, and the electroluminance is simulated by multiplying the emittance and photoluminance for the EMLs. The contour map elucidates the rationale for positioning the red device stack first on the anode. To position the red EML at the dotted circle annotated by 'R' with respect to the vertical axis, the four-stack WOLED employs a thin ITO anode, whose thickness is half of the thickness for the three-stack WOLED, contributing to enhanced blue efficiency, as will be explained later.

3. Green Device with Long Lifetime

The new WOLED incorporates independent phosphorescent red stack and green stack, which naturally enhanced the efficiency of the red and green subpixels but necessitate a long lifetime phosphorescent green device. Both the latest three-stack WOLED and our initial two-stack WOLED has utilized phosphorescent YG EML due to its exceptionally long lifetime. When developing the new WOLED without YG EML, one of the critical challenges was the short lifespan of the phosphorescent green device.

To extend the lifetime of the green device, innovations were made in both the green dopant and host materials. Figure 3 compares the EL spectrum and performance of green devices

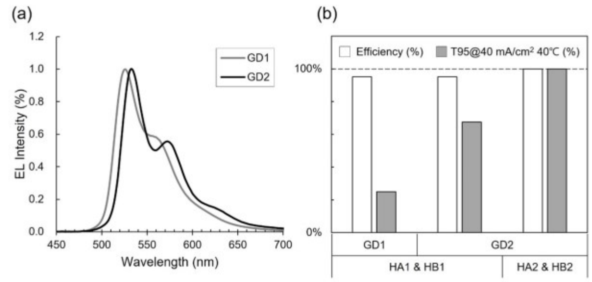

Figure 3. (a) Normalized EL spectra for mono green devices (b) Comparisons of efficiency and lifetime of the devices.

between the three-stack WOLED and the four-stack WOLED. Compared to the green dopant (GD1) used in the three-stack WOLED, the new green dopant (GD2) exhibits a similar FWHM but a redshifted λ_{max} by 6 nm, which is preferable for increasing the device lifetime. The new dopant is also expected to have ligands with high stability against polaron-triplet and triplet-triplet interactions. As a result, the new dopant enhances the lifetime of the green device by three times in the same host system (HA1 & HB1).

Regarding green hosts, two approaches were explored. The first approach was to identify a mixed host system that matches well with the new green dopant in terms of lifetime. In this case, a unipolar p-type host and an n-type host with weak bipolar characteristics were found to be the best combination. By varying the ratio of the two hosts and the dopant, the optimal condition for the lifetime was achieved. The second approach involved deuterating the host materials. By combining the innovative dopant (GD2) and hosts (HA2 &HB2) in the green device, we were ultimately able to enhance the lifetime by four times, making it comparable to the YG device.

4. Blue Device with High Efficiency

As it is well known, OLED panels utilizing WOLED technology consist of four subpixels in each pixel: red, green, blue, and white. Since the white subpixel has no color filter below the anode, the panel leverages the high efficiency of WOLED, thereby reducing power consumption. The color coordinates of the white subpixel should closely match the white pattern specifications of the OLED panel, which corresponds to a color temperature of 10,000 K or higher. This alignment allows the panel to reduce the electric current flowing into the other subpixels, which have lower efficiency than the white subpixel. To maintain the color temperature of the white subpixel, enhancing the blue efficiency is crucial in the four-stack tandem

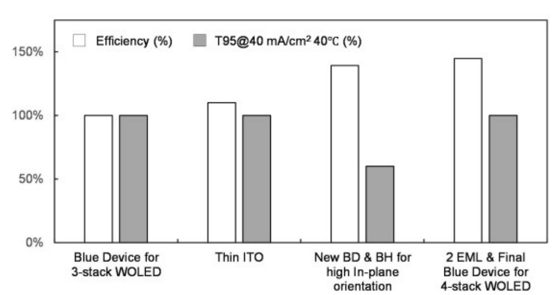

Figure 4. Break-down of enhancement of efficiency and lifetime in blue device for 4-stack WOLED.

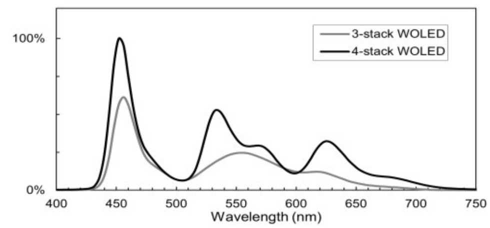

Figure 5. EL spectra of 3-stack and 4-stack WOLED at 10 mA/cm^2.

Table 1. Electro-optical properties of 3-stack and 4-stack WOLEDs at 10 mA/cm^2

	V	cd/A	x	y	CCT (K)
3-stack WOLED	11.1	82.8	0.282	0.293	9,600
4-stack WOLED	13.4	134	0.283	0.297	9,300

WOLED, as increased intensity in the red and green wavelength regions contributes to a warmer white color.

The four-stack tandem WOLED was able to enhance its blue efficiency with three major approaches. Firstly, as mentioned in Section 2, adopting a thin ITO anode with a thickness that maximizes constructive inference at the blue wavelength can increase blue efficiency by at least 10%, as depicted in Fig. 4.

Secondly, improving the in-plane orientation alignment of the transition dipole of the fluorescent blue dopant is essential. The new blue dopant is designed with a molecular structure that favors in-plane orientation. Blue hosts were developed to support in-plane orientation by raising their glass transition temperature (T_g). Additionally, optimizing the environmental condition during the evaporation process in the production also contributed to in-plane alignment.

Lastly, maximizing the triplet-triplet fusion by utilizing a two-EML structure,[13,14] where the first blue EML uses a pyrene host and the second EML uses an anthracene host, is another approach. The triplet energy of the pyrene host in the first EML is significantly higher than that of the anthracene host, allowing the triplet in the first EML to transfer easily to the second EML via Dexter energy transfer (DET). This process improves efficiency finally through the triplet-triplet fusion in the second EML. Furthermore, the two-EML structure drastically enhances lifetime of the blue device by alleviating excitonic stress near the HTL and EML interface, which fully recovered the lifetime reduced by the application of the new highly efficient blue dopant, shown in Fig. 4. Consequently, the blue efficiency in the four-stack WOLED can be enhanced by 45% without compromising the lifetime through these three approaches.

Table 2. Efficiency and color point of RGB subpixels for OLED panels employing 3-stack and 4-stack WOLEDs

		3-stack WOLED	4-stack WOLED
Efficiency (cd/A)	R	7.8	17
	G	27	57
	B	4.8	6.7
Color point in 1931 CIE (x, y)	R	0.679, 0320	0.690, 0.309
	G	0.269,0.679	0.249, 0.707
	B	0.146,0.051	0.149, 0.043
Coverage (%)	DCI	99.1	99.8
	BT2020	75.4	83.3

Table 3. Specifications of OLED TV employing the four-stack tandem WOLED.

Specifications	Contents
Size	48”, 55”, 65”, 77”, 83”
Resolution	3840 x 2160
Luminance (Flash peak / APL 3 /10 / 25 / 100%)	4,000 / 2,900 / 2,200 / 1,000 / 400 nits
Refresh rate	144 Hz
Color depth	10 bit

5. Performance of 4-stack WOLED

Figure 5 presents a comparison of the EL spectra between three-stack and four-stack WOLED at an identical current density of 10 mA/cm^2. The four-stack WOLED exhibits high intensity across the entire visible spectrum, ranging from blue to red color. As detailed in Table 1, the efficiency of the four-stack WOLED is enhanced by 60%, attributed to the independent formation of phosphorescent red and green stacks. The improvement in blue efficiency mitigates the shift in color point and correlated color temperature (CCT). Although the operation voltage increases with the number of stacks, the voltage rise in our four-stack WOLED was limited to 2.3 V by optimizing the thicknesses of EMLs and charge transport layers.

Table 2 provides a summary of the efficiencies and color points of red, green, and blue subpixels in the OLED panel utilizing the four-stack WOLED. The efficiencies of the red, green, and blue subpixels are enhanced by 110, 105, and 40%, respectively, with the four-stack WOLED. For the blue subpixel, the effective efficiency calculated as the efficiency (cd/A) divided by the color coordinate, 1931 CIE y is improved by 65%. Color points of red and green subpixels in the four-stack WOLED are shifted toward deeper colors. According to the BT2020 standard, the color gamut coverage area is expanded to 83%, despite employing the weak cavity structure.

Five new OLED TV models, ranging from 48” to 83” in size as listed in Table 3, are now available, each featuring the four-stack WOLED. Thanks to the high efficiency of the four-stack WOLED, these OLED TVs can achieve a maximum luminance of 4,000 nits at the flash peak as well as 2,900, 2,200, 1,000, and 400 nits at the APL (average picture level) of 3, 10, 25, and 100%, respectively. The models have the UHD resolution, refresh rate of 144 Hz, and color bit of 10 bits.

The improved efficiency and color gamut of the new WOLED, are expected to expand the potential applications of OLED displays, including IT displays. The four-stack tandem WOLED is planned to be used in gaming OLED monitor, targeting the high-end gaming market with a diverse range of panels in terms of size and aspect ratio as well as refresh rate which is the important specification for gaming monitors. The gaming OLED monitors feature bendable panels that adjust their curvature based on the gaming content.

6. Conclusion

In addition to reviewing the structural change of WOLED for TV display, this paper has detailed the recent innovations for the four-stack tandem WOLED. Despite of skepticism and challenges on the potential of WOLED technology, we have successfully demonstrated its capabilities through the numerous innovative advancements. Furthermore, as materials and device technologies advance, we anticipate that WOLED technology will continue to break new ground beyond its current performances.

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