Invited Talk: Advances in White OLED Tandem Architecture for Next Generation AMOLED Displays

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Abstract

Advances in white OLED tandem architecture are discussed. With these structures, stable and low-power full color AMOLED displays can be fabricated that are anticipated to be suitable for large area applications such as TVs. With a tandem architecture, efficient (24 cd/A) OLED structures with exceptional stability (~100,000 h at 1000 cd/m^2) are described. In addition, excellent color gamut (>100% NTSC) can be attained by incorporating advanced color filters into the AMOLED backplane in a typical bottom-emitting configuration.

1. Introduction

Small passive and active-matrix OLED displays have been commercialized for mobile applications and it is expected that OLED based displays will appear in larger display applications in the near future. To this end, large area prototype displays have been demonstrated by various organizations such as a 13" display by Sony Corporation [1], a 15" display by Kodak/Sanyo [2], a 20" display by IBM/CMO [3], a 40" display by Samsung Electronics [4], and recently a 25" display by CMO [5] and a 27" display by Sony [6]. Although these are key demonstrations that illustrate that AMOLED displays have many desired attributes, three critical issues remain that must be addressed in order for successful commercialization of large OLED displays: (1) TFT backplane performance and cost, (2) OLED display architecture meeting display performance (power, lifetime, and color gamut), and (3) efficient low cost OLED manufacturing (deposition) processes. All of these issues need to be resolved in order for AMOLED displays to compete in the large display marketplace, which is currently dominated by AMLCDs and PDPs.

This paper primarily discusses the OLED architecture. As we have described previously, issues with manufacturing yield and unit manufacturing cost (UMC) have prompted us to explore white OLEDs with color filters and we have demonstrated that this is a preferred format for large-area AMOLED displays. The white OLED emitting structure enables high-speed manufacturing by the elimination of precision shadow masking typically used to pattern the individual RGB emitters, reduces the number of defects, and allows the use of large-size substrates (shadow masking becomes progressively more difficult as the substrate size increases). Key to white-emitter based AMOLED displays is a high efficiency white structure, and this paper discusses the progress in white OLED technology useful for the four-sub-pixel RGBW display format including newly developed tandem architectures for improving efficiency, lifetime, and color gamut. With respect to color gamut, it is important that the emission from the white OLED structure matches well with the color filter optical characteristics. To this end, we have developed new color filters optimized to achieve >100% NTSC gamut ratio when combined with the tandem white emitting structure.

2. Results and Discussion

2.1 Performance Improvements in White OLED Formulation

Figure 1 shows the progress in performance of simple two-layer single stack white structures developed by Kodak. These results are based on fluorescent hosts and dopants incorporated into a two-emission layer yellow/blue (Y/B) configuration [8, 9]. As is clearly shown, the performance has continuously been improved, culminating in a low voltage (4.2 V), highly efficient (12 cd/A) and stable (50,000 h) structure discussed recently [10]. Because of the lack of a green emission peak, the Y/B white structure is deficient in color gamut. To correct for this deficiency, a three-emitting layer structure (R/B/G) was created by replacing the yellow-emitting layer with red- and green-emitting layers. This device resulted in improved color gamut, attributed to both the presence of a well-defined green emission band and a deep red emission at 610 nm; however, the efficiency was compromised (7.2 cd/A). A significant efficiency improvement (9.3 cd/A) was realized by using a four-layer R/Y/B/G structure [11] in which a Y layer was inserted into the structure. All of these gamut-improved structures operate at voltages in the 4-4.5 V range (at 20mA/cm^2).

These low-voltage single stack configurations have been applied to two stack (tandem) white emitting structures. Tandem structures provide higher luminous efficiency (~2X cd/A for a two stack tandem structure compared to a single stack) as well as significantly improved operational stability as a consequence of the lower current density required to produce the same luminance. Use of the low voltage single stack configurations in the tandem architecture is important to reduce the voltage required for the tandem structure, which is typically about twice that of a single stack. There are, of course, many possible combinations using the two-, three-, and four-layer emitting structures in this two-stack format, and we have investigated the various configurations in order to understand the trade-offs that exist between efficiency and color gamut [12]. The highest luminance efficiency combination is a two-stack Y/B + Y/B structure, but this also has the poorest color gamut, again as a result of the lack of a green emission peak. Adding R and G layers to improve the gamut in an R/Y/B/G + R/Y/B/G configuration provides excellent operational stability and color gamut (70% NTSC using standard LCD filters), however the efficiency was only about 16 cd/A. The primary reason for the low efficiency of this structure is the fact that it is difficult (nearly impossible) to optimally position both of the identical emitting zones within the OLED structure with respect to the reflective cathode. In order to investigate this issue, alternative structures were designed where the emitting regions in each of the stack are dissimilar, and can be positioned more optimally to the reflector. These structures are described in the next section.

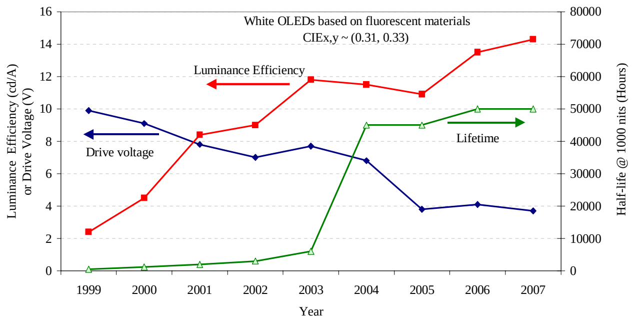

Fig. 1. Performance improvement of two-layer (Y/B) emitting white OLED based on fluorescent materials

2.2 New High-Efficiency Tandem White

Figure 2 shows the cross section of a tandem structure with dissimilar emitting zones. In this architecture, neither of the emitting stacks emits white, but the combined emission provides a broadband white spectrum with R, G, B and Y emission peaks.

Figure 3 shows the emission spectra for the individual emitting stacks in the tandem structure, with the first stack emitting mainly in the blue and the second stack emitting in the G–R region. Figure 4 compares the EL spectra of the newly developed two-stack tandem vs. that published earlier ("standard 2-stack optimized tandem") [12]. The earlier 2-stack tandem was based on a Y/B + R/Y/B combination, where each emitting stack was tuned to white. Essentially all the major peaks are at the same location except the intensity of the G, Y, and R peaks are higher in the new architecture.

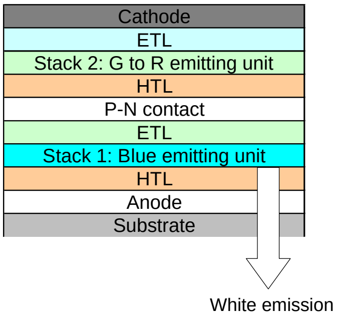

Fig. 2. Schematic of two-stack tandem architecture

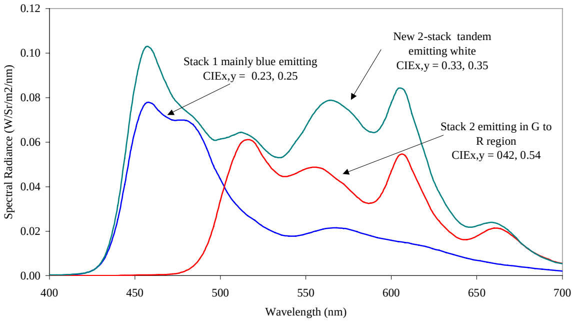

Fig. 3. EL spectrum of the individual emitting units and the combined white spectrum of the new two-stack tandem

Figure 5 compares the performance of the new high-efficiency two-stack tandem white to the standard two-stack optimized tandem white structure. While the standard tandem white shows a reasonable efficiency (16 cd/A) and color (0.31, 0.34), the new tandem white has significantly higher efficiency (24 cd/A) with a good white color (0.32, 0.35). This high performance was obtained by a combination of innovative architecture and new materials. The key architectural feature is that the emitting zones were optimally placed within the structure with respect to the reflective cathode.

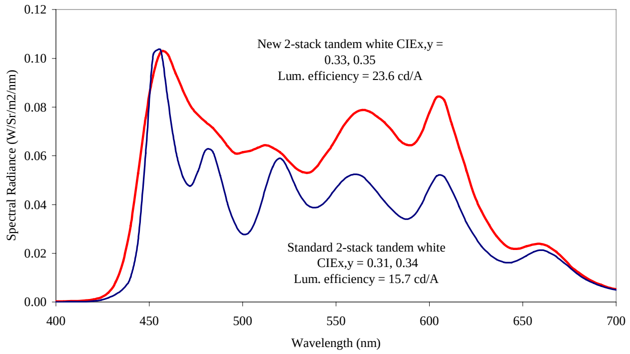

Fig. 4. Comparison of the EL spectra of the new formulation along with earlier two-stack tandem

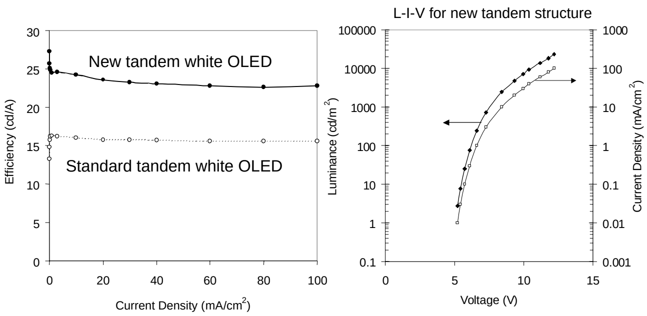

Fig. 5. Comparison of standard tandem white (dashed lines) vs. new high-efficiency tandem white (solid lines)

2.3 Stability Evaluation

We have evaluated the operational stability of the optimized two-stack tandem white OLED device by aging test structures at constant current density with starting luminance levels from 1000 cd/m^2 to 18,800 cd/m^2.

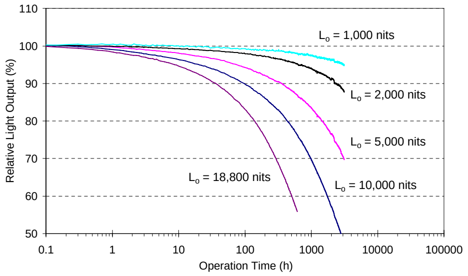

Fig. 6. Operational stability at different initial luminance

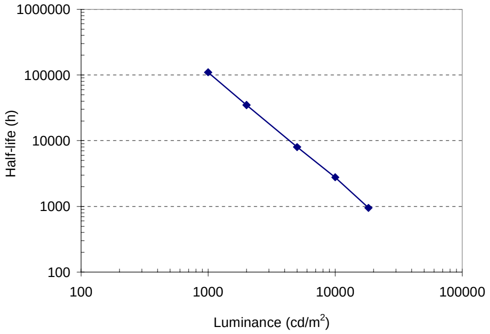

Fig. 7. Half- life vs. initial luminance

Figure 6 shows the luminance vs. time at these conditions. The half-life measured at 80 mA/cm^2 (18,800 nits initial luminance), for example, was over 900 h. We estimate the lifetime at 1000 nits to be >100,000 h. Figure 7 shows the half-life time as a function of luminance level. Note that the lifetimes at lower luminance levels are extrapolated from the stability plots shown in Figure 6.

We also studied the color shift of the two-stack tandem white OLED device with aging. Figure 8 shows the white EL spectrum before and after operating a device at 40ºC and 80 mA/cm^2 DC. The color is very stable over time, with a shift of only <0.015 Δu'v' at 50% initial luminance.

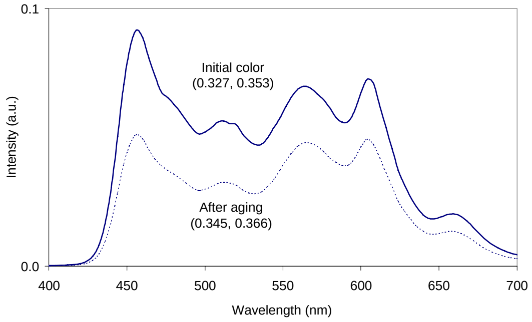

Fig. 8. Effect of aging on the EL spectrum

2.4 Color Gamut Improvement

While a well-tuned white OLED spectrum can achieve good color gamut with typical LCD TV color filters, it is difficult to increase the color gamut to greater than 80–85% NTSC ratio by further improvements to the OLED emission spectrum. This is due to the fairly broad nature of both commercially available LCD color filters and the OLED emission. In order to address this issue, Kodak has developed a set of customized color filters with optimized transmittance that achieve greater than 100% NTSC ratio when combined with the tandem white OLED emission [13].

Figure 9 shows the optimized two-stack tandem white emission spectrum along with typical LCD color filters (dashed lines) and the improved filters developed by Kodak (bold lines). The narrow bandwidth of the B & G filters and the sharper cutting edge of the R filter are responsible for the improved color purity. The R, G, and B emission spectra obtained by transmitting the white spectrum through the color filter spectra can be seen in Figure 10.

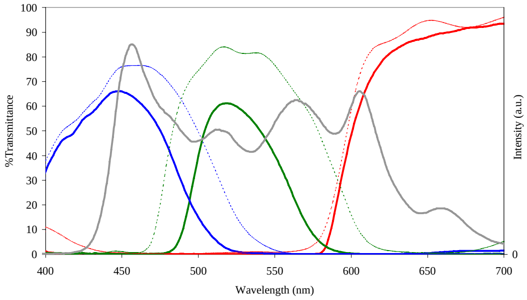

Fig. 9. RGB emission spectra, chromaticity, and color gamut obtained from commercial LCD (dashed lines) and Kodak's color filters (solid lines)

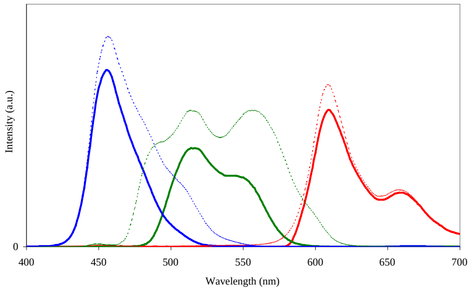

Fig. 10. RGB emission spectra from commercial LCD color filters (dashed lines) and Kodak's color filters (bold lines)

The chromaticity, efficiency, and color gamut obtained with these primaries are shown in Table 2. The new tandem format maintains the excellent color gamut of the earlier tandem architecture while improving the efficiency of the R, G, and B primaries. Although the R, G, and B efficiencies are reduced significantly for the Kodak OLED filters compared to the LCD filters, the overall display power consumption increases by only 10–20% as a result of the more saturated colors and the benefit of the RGBW sub-pixel format (where the unfiltered W pixel provides most of the luminance to the display). It is important to recognize that with the RGBW display configuration, the efficiency of the primary colors is not as critical to the overall display power, which is a consequence of the fact that very little of a typical image is color saturated, meaning that the W sub-pixel is used predominantly. Consequently, since this sub-pixel is not filtered and the white is highly efficient, the overall display power required can be low [14].

Table 2. Comparison of chromaticity, efficiency, and gamut for new tandem white OLED vs. earlier architecture

		Red			Green			Blue			Color Gamut	
White Emitter	Color Filter Set	Eff (cd/A)	CIEx	CIEy	Eff (cd/A)	CIEx	CIEy	Eff (cd/A)	CIEx	CIEy	NTSC xy Ratio	NTSC u'v' Ratio
Current Tandem White	LCD TV Filters	2.44	0.647	0.343	8.82	0.276	0.592	1.67	0.130	0.111	67.7	68.7
	Kodak's Filters	1.95	0.663	0.332	4.22	0.208	0.708	0.63	0.139	0.057	101.2	109.5
New High-Efficiency Tandem White	LCD TV Filters	3.93	0.645	0.345	12.82	0.293	0.582	2.33	0.130	0.111	64.5	66.1
	Kodak's Filters	2.35	0.665	0.331	4.25	0.204	0.704	0.76	0.139	0.057	101.2	110.3

Figure 11 shows the 1931 CIE and 1976 CIE chromaticity plots with the color triangles obtained with a combination of the tandem white OLED and typical LCD color filters and with the improved OLED filters designed by Kodak. The NTSC primaries are also shown. As is clearly seen, the green and blue primaries are dramatically improved using the Kodak OLED filters. The improvement in the blue is especially evident in u'-v' space, where the blue primary significantly exceeds the NTSC blue. It is actually closer to the Rec709 blue primary, resulting in a color gamut that is nearly 110% NTSCu'v' ratio. The exceptionally narrow, sharp cutting green filter and minimum overlap between the B and G filters are the key enablers for achieving the high color gamut. This demonstrates that the use of white tandem technology combined with properly designed color filters can provide AMOLED displays with color gamut exceeding 100% NTSC ratio. Note that the best color gamut that can be obtained by patterned RGB emitters without color filters is typically in the 80–85% NTSC ratio range. This is another key advantage of white OLED plus color filter technology.

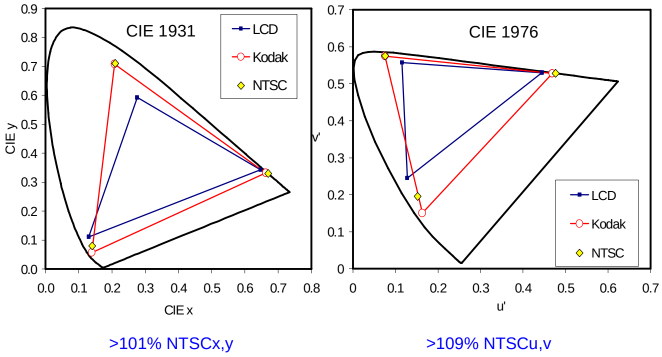

Fig. 11. Chromaticity plots showing enhanced color gamut obtained from a combination of new tandem white and Kodak's customized color filters

We simulated the performance of these tandem white OLEDs in a 32" a-Si TV application (RGBW pixel pattern, 450 nits peak luminance, no polarizer, bottom-emission, and Kodak's color filters). As described in earlier publications, full-color AMOLED displays using a white emitter with an RGBW pixel pattern provide a substantial reduction in power consumption for imaging applications [14, 15]. As shown in Table 3, both tandem whites achieve excellent color gamut (>100% NTSCx,y ratio), but the new tandem device achieves a 33% reduction in power consumption (41 vs. 61 W) as well as a remarkable 163% improvement in display lifetime (180,000 h vs. 68,000 h). The improvement in power consumption is a direct result of the higher efficiency of the white emitter. The lifetime improvement also results from the higher efficiency, which enables the display to operate at a much lower average current density, as well as the improved stability of the white emitter.

Table 3. Comparison of new tandem white OLED vs. earlier standard tandem architecture for 32" OLED TV

	Parameter	**Standard 2-stack tandem**	**New high efficiency tandem**
Device Performance @20 mA/cm2	Luminance effiicency	15.7 cd/A	23.6 cd/A
	White Point (CIEx,y)	0.31, 0.34	0.32, 0.35
	Drive voltage	8.5 V	9.3 V
	Operational stability @ 80 mA/cm2	800 Hrs @ Lo = 12,560 cd/m2	1000 Hrs @ 18,800 cd/m2
Display Performance simulated for 32" a-Si AMOLED TV **Display peak luminance = 500 cd/m2, No polarizer, ~ 0.50 pixel aperature ratio, Kodak narrow band color filters**	Average power consumption	61 Watts	41 Watts
	Life time	68,467 h	180,231 h
	Color Gamut (NTSCx,y ratio)	102%	102%

3. Conclusions

Highly efficient and stable tandem white OLED structures with emission close to D65 and emission peaks tuned to match optimized color filters have been developed. Key to the high efficiency is the incorporation of dissimilar emission zones in each of the stacks that make up the two-stack tandem structure, placed optimally with respect to the reflective cathode. With such a structure, an efficiency of 24 cd/A has been realized, with CIE x,y of (0.33,0.35). The white tandem technology described in this paper, combined with the optimized color filters, can provide TV-sized (32") AMOLED displays with low power consumption (<50 W) at high peak luminance (>500 cd/m^2), wide color gamut (>100% NTSCx,y), and long lifetimes (>100,000 h). With its natural performance advantage of very high contrast, thin architecture, and excellent off-axis viewability, OLED display technology is poised to compete successfully with other large flat-panel display technologies such as LCD and PDP.

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5. References

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