1447: High Performance Tandem OLEDs for Large Area Full Color AM Displays and Lighting Applications

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Abstract

Tandem OLED structures formed by connecting two or more low-voltage electroluminescent units (stacks) are effective for achieving high efficiency at low current density as well as long operational lifetime. We have fabricated white emitting tandem structures with two or three low-voltage white-emitting stacks using transparent organic "PN"-type connectors. Three- stack white tandem structures with efficiency greater than 24 cd/A at D65 and operational stability of about 110,000 h. (extrapolated) at 1000 cd/m^2 have been demonstrated. With a stacked structure, the power consumption for displays using an RGBW format can be reduced by 25% compared to previously described formulations. We have also fabricated advanced white tandem structures where the color gamut (NTSC x,y ratio) has been improved to greater than 70% using standard color filters. The white OLEDs can also be used to increase the color-rendering index CRI (>80%), an important consideration for solid-state lighting.

1. Introduction

OLED technology has been commercialized for full -color active- and passive- matrix displays [1-3]. Since the first demonstration of 2.4" full color AMOLED displays by Eastman Kodak in 2000, the pace of technological development directed toward larger OLED display applications such as notebook PCs and TVs has accelerated, driven largely by the substantial revenue opportunity in this market segment. For example, Samsung Electronics recently demonstrated a 40" full color AMOLED display prototype [4]. Others have also prototyped large displays; including a 20" amorphous silicon based display from IBM/Chi-Mei [5] and a 24" LTPS based AMOLED from Sony [6]. It is imperative, however, that display performance meets the specifications for power efficiency, lifetime, color gamut, and display luminance in order to be competitive with the well established LCD and PDP technologies. To be successful, careful selection of the OLED device architecture, the method of manufacturing, and the backplane design is required.

Arguably, the most important factor that will determine whether OLED displays are widely adopted is manufacturing cost. It has been recognized that direct emitter patterning by shadow masking is costly as well as cumbersome and probably not scaleable to larger substrate sizes due to thermal expansion issues. Additionally, the yield is likely to be negatively impacted by the direct contact of the shadow mask to the AM backplane. This prompted Kodak and Sanyo Electric to investigate white OLED emission with RGB color filters, resulting in the demonstration of a 14.7" full color display at CEATEC in 2002 [7]. In this format, the white emitter is applied over the entire display surface and the R, G and B emission results from the color filter array that is formed on the backplane (prior to the OLED layer depositions). This architecture is suitable for the higher generation substrate sizes required for large display manufacturing. Other means of RGB patterning such as inkjet printing or laser transfer- are currently being investigated but both of these techniques suffer from technical issues that remain to be resolved.

Although full color displays are easily fabricated using white emission and RGB color filters, the power consumption of this format is too high as a consequence of over 70% of the emission being internally absorbed by the filters. In order to overcome this problem, an RGBW format has been developed that reduces the power consumption substantially [8]. Key to this improvement is a high-efficiency white emitter optimized to the target display white point (in this case D65). With the RGBW format, the power consumption is reduced to approximately 50% of the analogous white emitter based RGB format. In order to lower the power consumption further (for either format), an increase in the white OLED efficiency is necessary. Additionally, the white spectrum should contain all of the relevant emission peaks, matching the R, G, and B color filters, in order to obtain a high color gamut. Significant progress has been made over the past several years in improving the white OLED performance to the point where an OLED TV is now technically feasible. In addition to AMOLED displays, there is also an opportunity for the RGBW format in passive matrix OLED displays (PMOLED) because of the same RGB emitter direct patterning difficulty. Furthermore, OLEDs are being considered for solid state as well as LCD backlighting. For all of these applications, a highly efficient, stable white emitter with the appropriate spectral properties is required.

Tandem architectures are known to be highly efficient and stable, and have been demonstrated for green and blue emissions [9,10]. With this architecture, the voltage is increased as the number of emission units is increased. In order to maintain the voltage within an acceptable range, low voltage emission units are required. This paper will discuss low voltage tandem white OLED structures that are useful for the RGBW display format as well as for lighting applications.

2. Results and Discussion

Recently, we have shown that full-color AMOLED displays using a white emitter with an RGBW pixel pattern provide a substantial reduction in power consumption for imaging applications compared to analogous displays with a white emitter and an RGB pixel pattern [8]. Figure 1 illustrates the basic RGB and RGBW architectures. In the RGBW format, an unfiltered white subpixel is provided in addition to the filtered RGB subpixels in order to boost the overall efficiency. Given that most images contain a significant amount of white or unsaturated colors, the highly efficient white pixel is consequently used frequently. This results in a power consumption of about one half that of the analogous white-based RGB display.

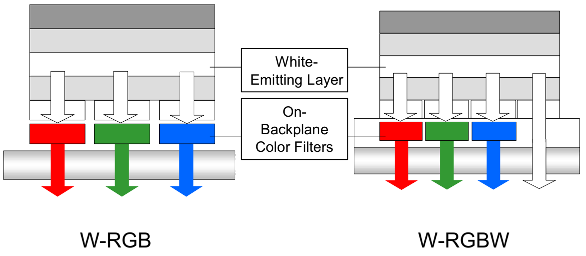


Figure 1. RGB and RGBW formats using an un-patterned white emitting OLED and color filter array

Key to the reduced power of the RGBW format is a high-efficiency white emitter optimized to the target display white point (usually D65). It is particularly important to match the chromaticity of the white emitter to the white point of the display for the RGBW format. This is illustrated in Figure 2, which uses modeled device data to show how the relative efficiency requirement changes with white emitter chromaticity in an RGBW device (where the power consumption and display luminance is held constant and the efficiency for a D65 white emitter is normalized to 1.00). Note that the efficiency requirement increases as the white emitter chromaticity deviates from D65. For example, an RGBW display with a (0.39, 0.33) white emitter chromaticity will require about twice the efficiency (cd/A) in comparison to an RGBW display with a D65 white emitter to produce the same display power consumption. From this figure, it is clear that both the efficiency (cd/A) and chromaticity (CIEx,y) must be optimized in order to achieve the lowest display power consumption. To this end, the efficiency optimizations of the tandem structures discussed in the following sections are aimed at the D65 white point.

Tandem white emitting structures were discussed earlier [11]. High efficiency at lower current density was obtained by joining multiple electroluminescent units (stacks) in series using an optically transparent "PN" connector between the adjacent stacks. With this format, since each of the emitting stacks is connected in series, the drive voltage increase is expected to be linearly proportional to the number of stacks included in the structure.

The quantum efficiency (photons emitted per electron injected) is also expected to increase linearly with the number of stacks, which results in a significant improvement in the operational stability (from the same initial luminance) as a result of the reduced current density required to produce the same luminance with the more efficient structures.

A three-stack white emitting structure is shown schematically in Figure 3, where the stacks are connected in series. In this figure each stack emits white, as a consequence of blue- and yellow-orange- emitting layers. In theory, if each white emitter stack gives luminance Lo at a constant current level of Io, the luminance level of the overall structure should be 3Lo. The "PN" connector is highly important in this structure and is typically fabricated using an organic and optically transparent material designed to provide the required carrier injections with essentially no voltage loss.

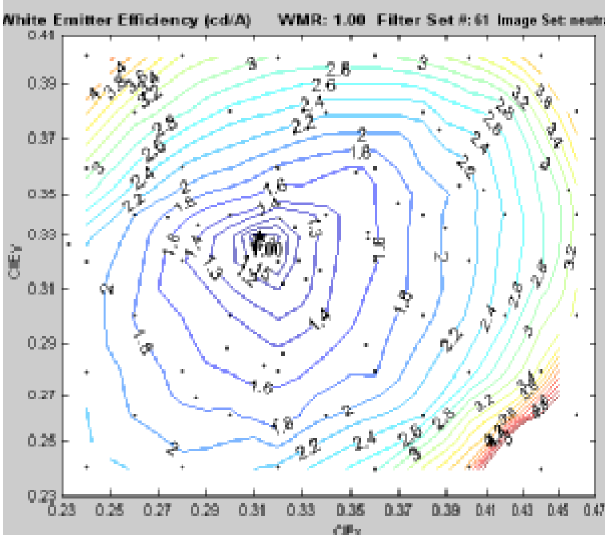


Figure 2. Relative white emitter efficiency (cd/A) required attaining equal RGBW display power at a constant luminance at a target display white point of D65.

Liao et al found that for green emitting tandem structures the luminance efficiency increased linearly with the number of stacks, which resulted in a significant improvement in the operational stability (from the same initial luminance) as a result of the reduced current density required with the more efficient structures [9,10]. Efficiencies of 32 cd/A and 136 cd/A were demonstrated for green fluorescent and phosphorescent devices, respectively, with three-stack tandem architecture. The drive voltages also increased linearly with the number of stacks and were greater than 20 V for the three stack fluorescent device and greater than 30 V for the three stack phosphorescent device (at 20 mA/cm^2). More recently, Liao et al has shown up to 38 cd/A efficiency for a greenish blue emitting tandem OLED [9]. In both the green and blue tandem structures, the emission color is the same as the single stack reference.

In order for the tandem architecture to be useful for display applications, the drive voltage should be minimized. This means that the voltage drop across each of the emitting units must be reduced so that the overall drive voltage (obtained by summing the voltage drop across each stack) is within an acceptable range that is compatible with the drive electronics and the power consumption specification for the display. As mentioned above, for display formats using a tandem white architecture, a low-voltage white emitting stack is required. Although highly stable with good efficiency, the single stack white emitting device developed previously required relatively high drive voltage and is not acceptable for the tandem architecture format. [12]. However, this structure exhibited an efficiency of 12.8 cd/A at D65 with an excellent stability (>50,000 h at 1000 cd/m^2). As discussed, however, the driving voltage was relatively high (~8V) and furthermore the color gamut was relatively low (~60% NTSCx,y).

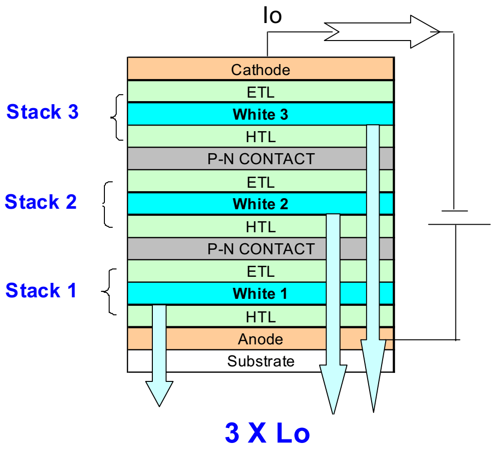
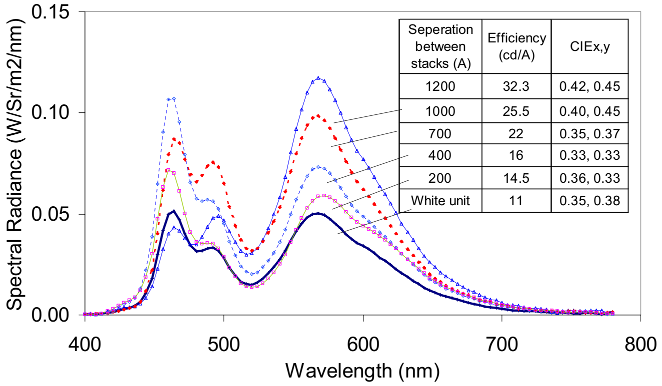


Figure 3. Tandem architecture with three- white emitting stacks.

The new low voltage white devices (single stack) operate at relatively low drive voltage (~ 3.5 V at 20 mA/cm2 current density) as a result of minimizing the layer thicknesses, the use of a new electron transport layer, and incorporating a more conductive blue host into the structure. The low-voltage white device has a similar emission spectrum to the higher voltage structure [12], with CIE x,y color coordinates of (0.32, 0.35) and luminance efficiency of 10.8 cd/A at 3.5 V and 20-mA/cm^2. A slight modification in the structure provided an efficiency of 15.2 cd/A at 3.3 V drive voltage, but with a slightly yellowish color (CIEx,y = 0.35, 0.38). These devices have excellent luminance and voltage stability during extended operation (discussed in a subsequent section). Others also have discussed low-voltage white formats with a single stack structure [13,14]. However, the operational stability was not discussed.

We have found that, unlike the monochrome green or blue devices, the luminance efficiency of the white tandem device does not linearly increase with the number of white-emitting stacks [11]. Both the luminance efficiency and the white point of the tandem structure depend strongly on the separation between the stacks. Figure 4 shows the EL spectra of two-stack tandem devices where the separation (D) between the two units was varied between 0 and 1400 Å. The single-stack control is shown by the solid curve and has a luminance efficiency of 11 cd/A at 20 mA/cm^2 with CIE x,y coordinates of 0.35, 0.38. Both the luminance efficiency and color varied significantly with the separation distance. In this example, the efficiency was as high as 25.5 cd/A and as low as 14.5 cd/A, however the chromaticity was not constant. This effect is caused by the complex optical interference that occurs within the structure, with the most important factors being the distance between the emitting units and the reflective cathode and between the emitters and the ITO/glass interface.



Seperation between stacks (A)	Efficiency (cd/A)	CIEx,y
1200	32.3	0.42, 0.45
1000	25.5	0.40, 0.45
700	22	0.35, 0.37
400	16	0.33, 0.33
200	14.5	0.36, 0.33
White unit	11	0.35, 0.38

Figure 4. EL spectra changes with varying separation (D) between the two stacks in a tandem OLED structure.

As discussed, it is important to optimize the white emission to D65 for displays with the RGBW format, and, to this end, we have adjusted the position and the white point of each stack in order to provide two-stack and three-stack tandem whites with an emitting color near D65. Figure 5 shows the EL spectra of one-, two- and three-unit tandem structures with chromaticity near D65 (measured at 20 mA/cm^2). The L-I-V curves for these devices are shown in Figure 5. The luminance efficiency, drive voltage, and chromaticity are given in Table 1. The single-stack device has an efficiency of 10.7 cd/A, a drive voltage of 4.2 V, and CIE x,y of 0.32, 0.35. The two-stack tandem device has an efficiency of 17.4 cd/A, drive voltage of 8.7 V, and CIE x,y of 0.30, 0.34 and the three-stack device has an efficiency of 24.6 cd/A, drive voltage of 13.1V, and CIE x,y of 0.32,0.34. These results give approximately 1.7X and 2.3X improvement in efficiency for the two stack and three stack tandem structures, respectively. The drive voltage, however, shows a linear increase with the number of stacks, which is similar to monochrome green devices [9]. The lack of linearity in the efficiency with the stack number is primarily due to the difficulty in optimizing both the yellow and blue-green portions of the emission spectrum at essentially the same emitting planes within the structure.

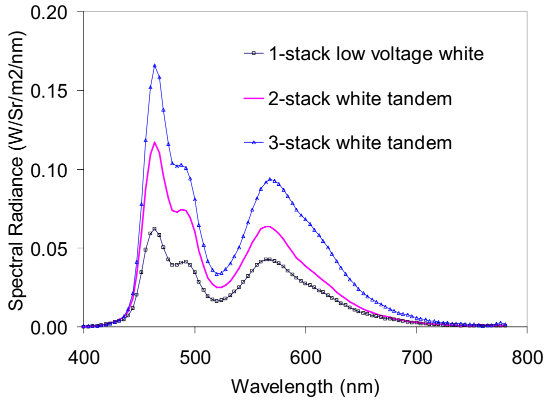


Figure 5. EL spectra for one-, two-, and three- stack white structures optimized for D65 white point.

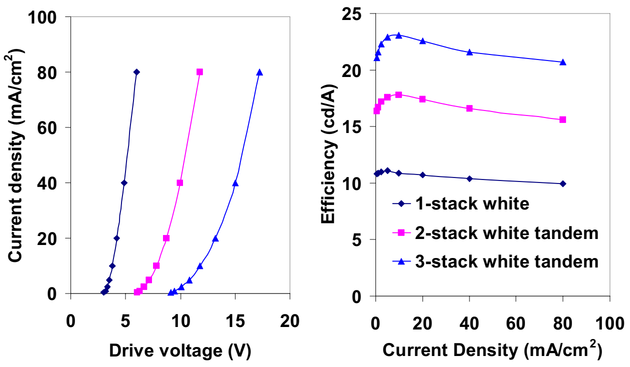


Figure 6. L-I-V characteristics of the one-, two-, and three-stack structures shown in Figure 4.

Table 1 shows the performance of the one-, two- and, three-stack tandem white OLED structures at 20 mA/cm^2 and the predicted power consumption modeled for 2.16-inch diagonal AMOLED displays with both the RGB and RGBW formats. The power consumption was predicted using a model developed to evaluate the performance of the various white formulations, using the white efficiency and spectral data as well as the drive voltage at the required current density as inputs to calculate the average power consumption required for a set of 13,000 digital camera images. In all cases, the target display white point was D65, the luminance was 180 cd/m^2, and the calculations included a circular polarizer with 44% transmittance. As shown, the improved luminance efficiency (cd/A) of the white emitter as the number of stacks increases results in lower power consumption, even though the efficiency does not increase linearly with the number of stacks. These results from the lower current density required producing the same display luminance for the higher efficiency configurations, with the consequence being that the increase in voltage is less than linear due to a lower operating point on the J-V curve.

Table 1. Performance of white tandem OLEDs

White Structures	Drive Voltage (V)	Luminance Efficiency (cd/A)	CIEx	CIEy	RGBW Power (mW)	RGB Power (mW)	NTSCxy Ratio
2-peak white (single stack)	8.0	11.0	0.326	0.332	289	657	61%
2-peak low voltage white (single stack)	4.2	10.7	0.320	0.350	228	527	63%
2-stack Tandem using 2-peak low voltage white	8.7	17.4	0.304	0.338	194	448	63%
3-stack Tandem using 2-peak low voltage white	13.1	24.6	0.320	0.336	172	409	62%
Advanced low voltage white (single stack)	4.3	9.9	0.318	0.348	236	557	71%
2-stack Tandem using advanced low voltage white	8.6	17.5	0.329	0.369	216	451	70%

In addition, the required display voltage does not increase linearly as more stacks are added since a fixed portion of the voltage is budgeted to drive the AM circuitry. The combination of the higher efficiency (cd/A) and lowered voltage (from both the lowered current density required and fixed overhead voltage) results in the overall reduction in display power as the number of stacks is increased.

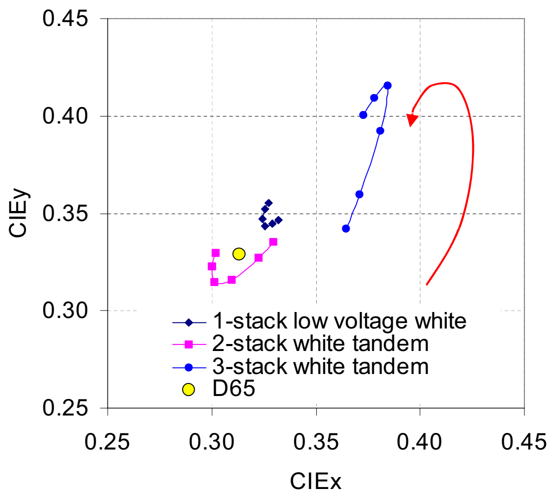


Figure 7. Angular color shift measured at (0-15-30-45-60-70^0) for one-, two-, and three- stack white structures

In addition to an optimized white point, the white OLED display must also be designed to have little or no perceptible color shift with viewing angle. Figure 7 shows the angular color shift measured for one-, two-, and three- stack tandem white structures. In all cases, the color shifts towards yellow and moves in the counter-clockwise direction indicated (as show by the directional arrow in Figure 7) when the display is viewed from a normal (zero degree) to an oblique angle (70 degree). The maximum color change occurs for the 3-stack tandem but is within an acceptable range.

These structures also show good operational stability for both luminance decay and voltage rise. Simple test devices (0.1 cm^2) were operated under DC conditions at initial luminance levels of 1000 and 5000 cd/m^2. Figure 8 shows the luminance stability as a function of operational time for the three devices shown in Figure 6. The stability of the new low voltage white OLED (single stack) is similar to the white structure published earlier [12], which operated at approximately twice the drive voltage at equivalent luminance levels. The luminance stability is significantly improved for the tandem structures because of the lower current density required for the same luminance level. After operating for over 4000 h, the extrapolated half-life time at 1000 cd/m^2 for the single stack low-voltage white OLED is expected to be >50,000 h; for the two-stack tandem structure, it is expected to exceed 70,000 h; and for the three EL-unit tandem structure, it is expected to exceed 110,000 h. Figure 9 shows the drive voltage change for these same devices. It is noteworthy that the drive voltage increases very slowly for all of these configurations, with an expected increase of less than 1 V when the luminance has decayed to half of the initial level.

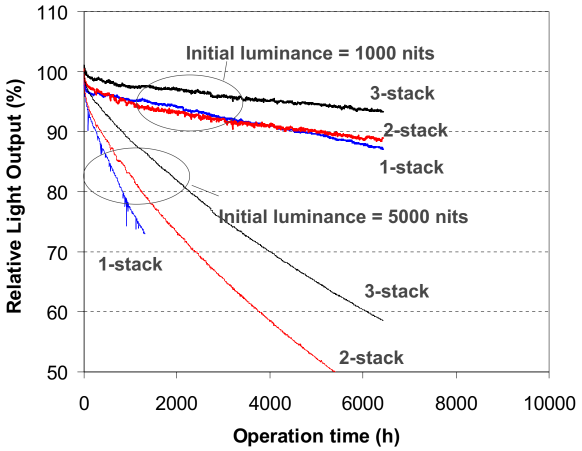


Figure 8. Luminance stability for one, two- and three-stack white tandems at initial luminance of 1000 and 5000 cd/m^2.

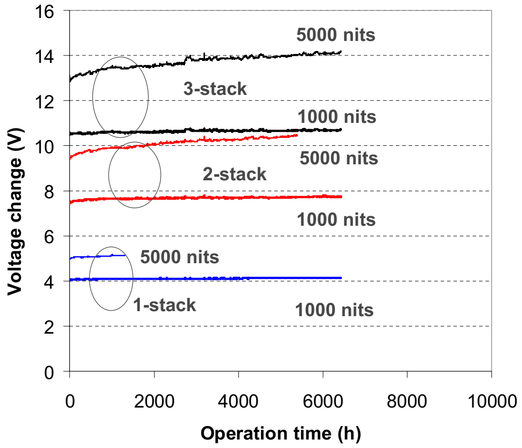


Figure 9. Voltage stability for 1, 2- and 3-stack white tandems at initial luminance of 1000 and 5000 cd/m^2. The voltage for the device was not corrected for ITO series resistance.

We have also developed white structures that provide an improved color gamut as well as low voltage and high efficiency. These white structures incorporate red and green emitting layers that were not present in the white structures shown in Figure 5 and show similar drive voltage, luminance efficiency, and stability to those devices. Figure 10 shows the EL spectra of the white single stack and two stack tandem structures designed for improved gamut. The operating characteristics as well as the predicted power consumption for a 2.16" display are included in Table 1. As shown, these structures ("advanced white") have slightly lower efficiency than the 2-layer white emitter but have better color gamut as a result of the emission peaks in the blue, green and red portions of the spectrum. relative to the two-peak white devices described earlier in this report. The color gamut is indicated in Table 1 and was calculated using typical LCD television color filters. For an RGBW full color display, a color gamut of >70% NTSC is achievable with this combination of OLED emission and color filters. Figure 11 shows the color gamut comparison for a two-peak white and the high gamut white structure. The NTSC color gamut triangle is also included.

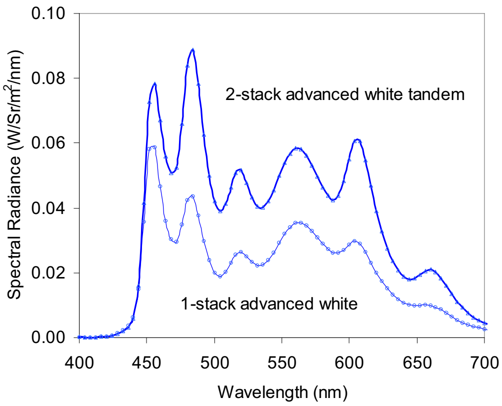


Figure 10: EL spectra for advanced white structures.

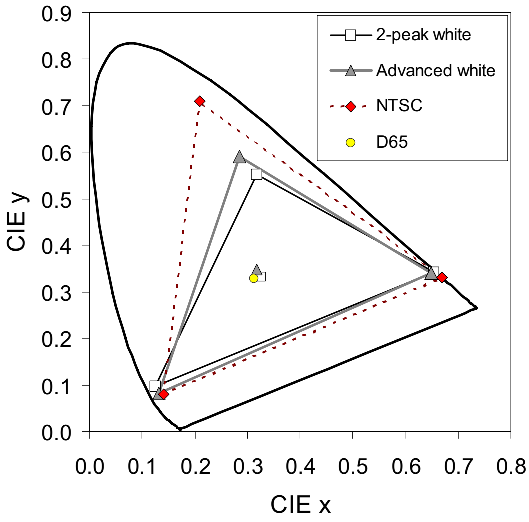


Figure 11. Improved color gamut with advanced white OLED

The white structures can also be used to tune the color-rendering index (CRI) of the white emission, an important consideration for solid-state lighting applications. Typically, it is difficult to obtain a high CRI from a single broadband emitter. By using various host-dopant combinations in the emitting layers and creative architectural designs, we have prepared white emitting OLED that produce CRI>80 in the color temperature range of 3000 – 6000 K. Figure 12 shows the emission spectra of two different white OLED structures where CRI of 82 and 88 were produced.

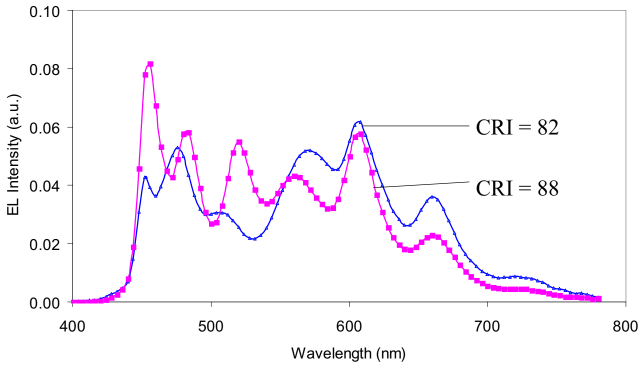


Figure 12: White OLEDs structures for improved CRI for solid-state lighting applications.

3. Summary and Future Outlook

In summary, we have increased the efficiency of the white OLED by using a tandem architecture. This results in a lower display power (calculated) compared to a single stack white emitting structure and is particularly useful for the RGBW display format. With a three-stack tandem structure, an efficiency greater than 24 cd/A at the D65 white point has been demonstrated, with an extrapolated half-lifetime near 110,000 h at 1000 cd/m^2. With this stack configuration, the power consumption for the RGBW display is reduced by 25% compared to the analogous single stack emitter. We have also fabricated advanced white tandem structures where the color gamut (NTSC x,y ratio) has been increased to greater than 70% using standard color filters. Additionally, we have shown that a color-rendering index CRI (>80%) can be attained, an important consideration for solid-state lighting.

It is expected that LCD technology will also make rapid progress over the next few years, where high color gamut (>100% NTSCxy ratio) will be the standard as a result of improvements in backlight technology (improved CCFLs and LED backlights). Therefore, OLED technology must be able to deliver the same or better performance at competitive cost. White OLED structures with RGB emission peaks that match an improved set of RGB color filters will be required to meet the high color gamut requirements, while simultaneously improving the power consumption and lifetime performance. The combination of high efficiency, long lifetime, high color gamut and the avoidance of the precision shadow masking process are attributes that make OLED displays based upon a white emitter highly attractive for manufacturing The improvements in the performance of the white OLED by the implementation of highly efficient tandem formats coupled with improved color filters will make the AMOLED technology a serious contender to LCD and PDP for large area displays.

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