White OLED Structures Optimized for RGB and RGBW Formats

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Abstract

White-emitting OLEDs have been prepared that provide emission close to 6500 K color temperature (D65) with exceptional stability and high efficiency. The combination of host and dopant materials offers significant improvement for full color displays, in terms of power consumption, with minimal changes in color and efficiency with current density. These features are important for fabricating RGB and RGBW full color displays using white OLEDs with color filters.

1. Introduction

Tremendous improvements have been made in efficiency, lifetime, and color purity of red, green, blue, and white-emitting OLEDs since efficient electroluminescence from organic thin films was first described in 1987 [1-3]. Recently, white OLEDs have been the focus of attention for many applications, including low-cost large-area light sources, back-lights in liquid-crystal displays [4,5] and full color displays using color filters. In the latter case, the R, G, and B color pixels are formed by patterning the color filters either on the TFT substrate (for a through-substrate bottom-emitting active-matrix OLED) or on the top of a transparent cathode (for a top-emitting structure). Although the color filtering drastically reduces the transmitted intensity, the high efficiency of the white OLED has led to performance that is comparable to displays based on pixelated R, G, and B emitters. The use of white OLEDs with color filter arrays for fabricating full color displays also offers manufacturing advantages, such as improved yield resulting from elimination of precision shadow mask related defects and shorter cycle time because the white OLED structure contains only two active layers (unpatterned) whereas three adjacent emitting layers are required using the patterned emitter approach. Through a joint development partnership between Eastman Kodak Company and SANYO Electric Co., Ltd., we earlier reported white OLED characteristics and demonstrated a 15" diagonal full color display [6]. In this report, we describe white formulations developed for another application of white OLEDS—fabrication of full color displays based on a RGBW four sub-pixel format. With this configuration, a fourth, white sub-pixel without a color filter is implemented. The high efficiency of the unfiltered white pixel improves the overall power efficiency and operational stability of this new display format.

2. Results and Discussion

The white OLED structure is shown in Figure 1. The hole and electron-transport layers consist of NPB and Alq, respectively. Both the blue-emitting and yellow-emitting layers incorporate host and dopant materials. In the case of the yellow layer, a single host is used with a yellow-emitting dopant as well as with an assist dopant. For the blue-emitting layer, a different host-dopant combination is used, but, similar to the yellow layer, a blue-assist dopant is incorporated. White emission is obtained by appropriately mixing the emission from the adjacent blue and yellow-emitting layers in the OLED multilayer stack. Mechanistically, charge recombination in the blue-emitting layer results in the formation of the blue dopant excited state, which then emits directly or transfers excited-state energy to the yellow-emitting layer. Partitioning of charge carrier recombination between the blue and yellow layers may also occur to some extent; however, regardless of the exact mechanism, the result is emission of both blue and yellow light, which when combined, results in white emission.

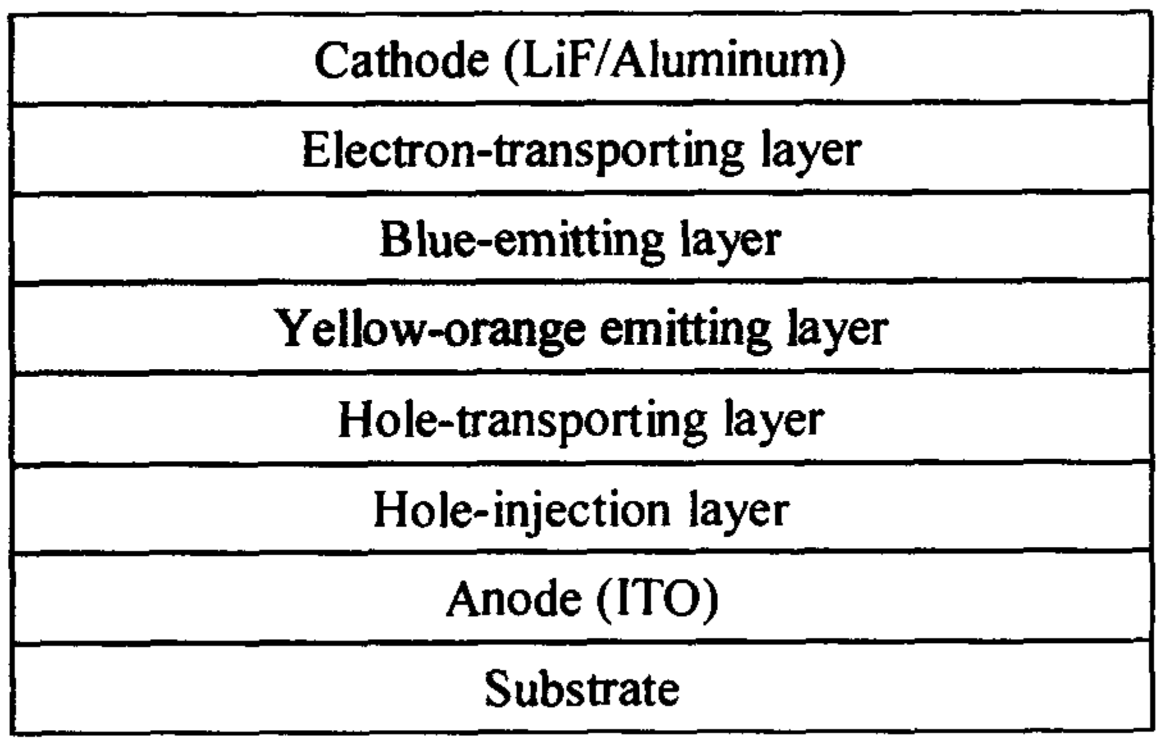

Figure 1. White OLED device structure

Figure 2 shows the EL spectra at various current densities for a white OLED with 1931 CIE coordinates as shown. The emission spectrum is quite insensitive to the current density; however, the yellow component tends to increase slightly with increasing current density, especially noticeable at 20 and 40 mA/cm^2. Typically, the color shift is no more than 0.02 units over this current density range.

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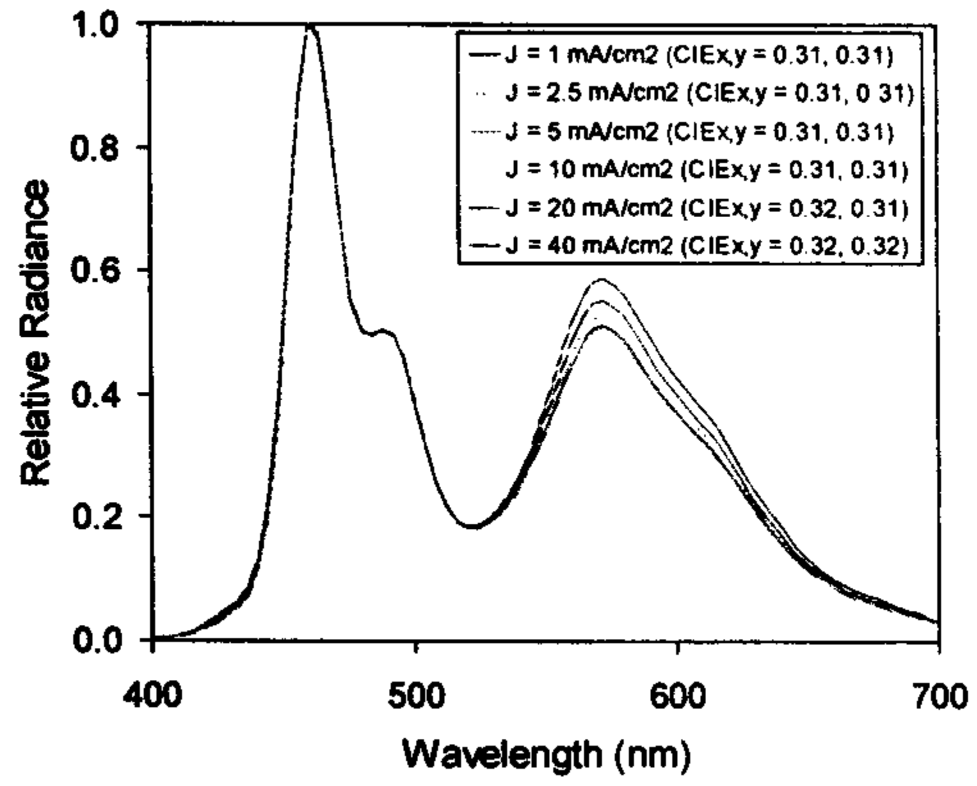

Figure 2. EL spectra at various current densities.

The hue of the emission can be modified by variation of the OLED structure (dopant concentrations, layer thicknesses, etc.) and tuned to the desired color temperature. Figures 3, 4, and 5 show the chromaticity as a function of concentration for the yellow, blue, and yellow assist dopants, respectively. In all three plots, the chromaticity was determined at 1, 2.5, 5, 10, 20, and 40 mA/cm^2, and a progressive yellow shift was observed for each device configuration with increasing current density. As shown in Figure 3, the yellow dopant concentration has a large effect on the white point (at a particular current density), and the optimum concentration (nearest to the D65 point) is at about 2%. The chromaticity is much less sensitive to the blue dopant concentration, as illustrated in Figure 4. In this case, the optimum concentration appears to be in the 0.5-1% range. As with the yellow dopant, as the concentration of the blue dopant is increased, the chromaticity change with current density also increases. With the yellow assist dopant (Figure 5), the optimum concentration from the standpoint of stability and efficiency (not shown) is in the 5%-10% range. In this range, the chromaticity change with current density is about the same as without incorporation of assist dopant. All three of these dopants show a similar trend in terms of the chromaticity change with current density. That is, as the dopant concentrations increase, the magnitude of the color shift increases. In all three graphs, the color shifts from left to right as current density increases from 1 to 40 mA/cm^2.

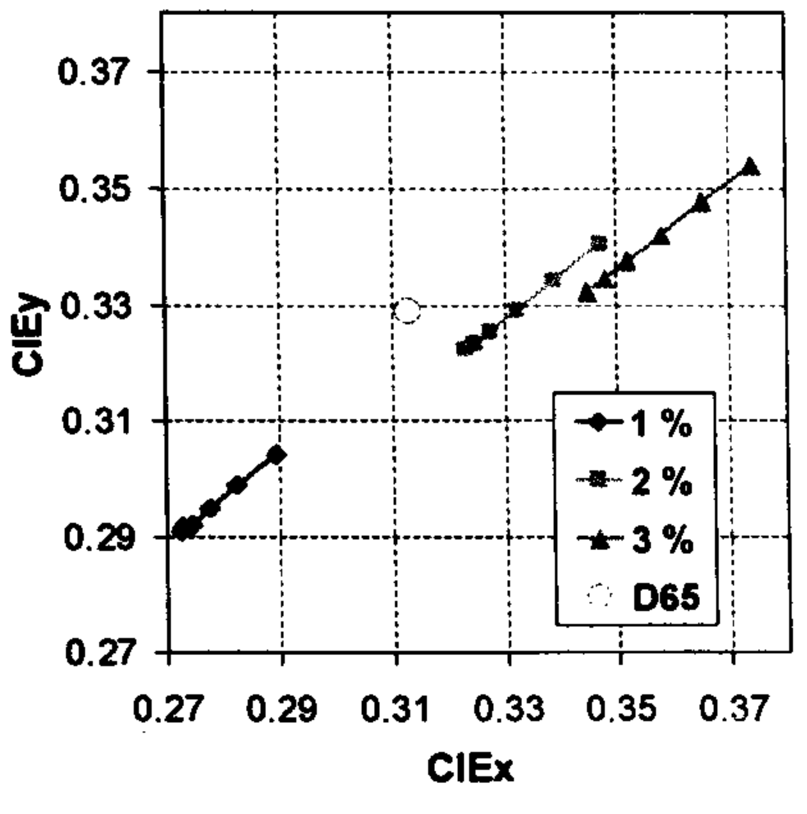

Figure 3. Effect of yellow dopant concentration on chromaticity as a function of current density.

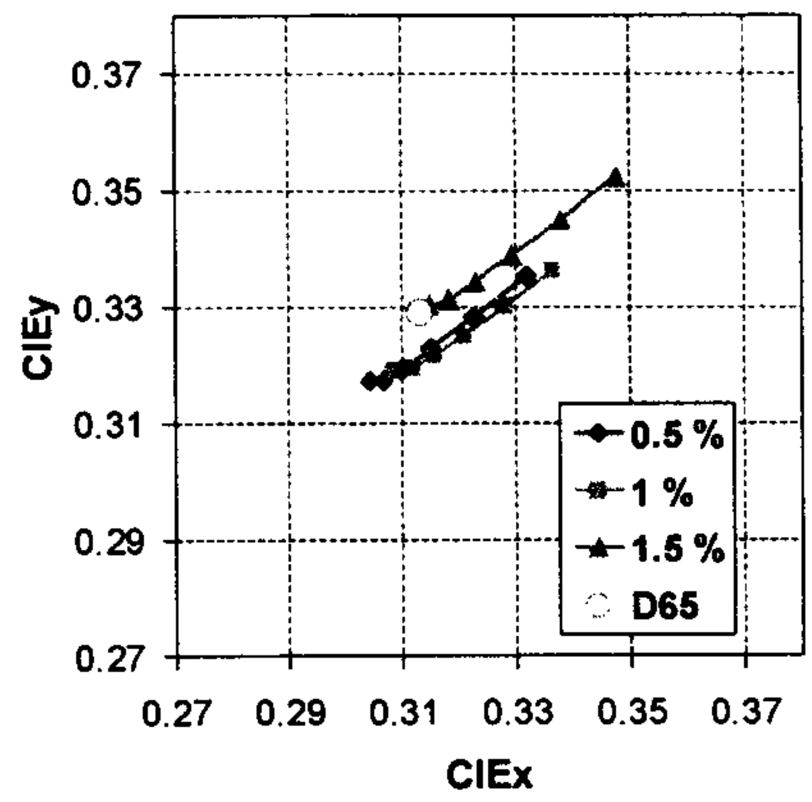

Figure 4. Effect of blue dopant concentration on chromaticity as a function of current density.

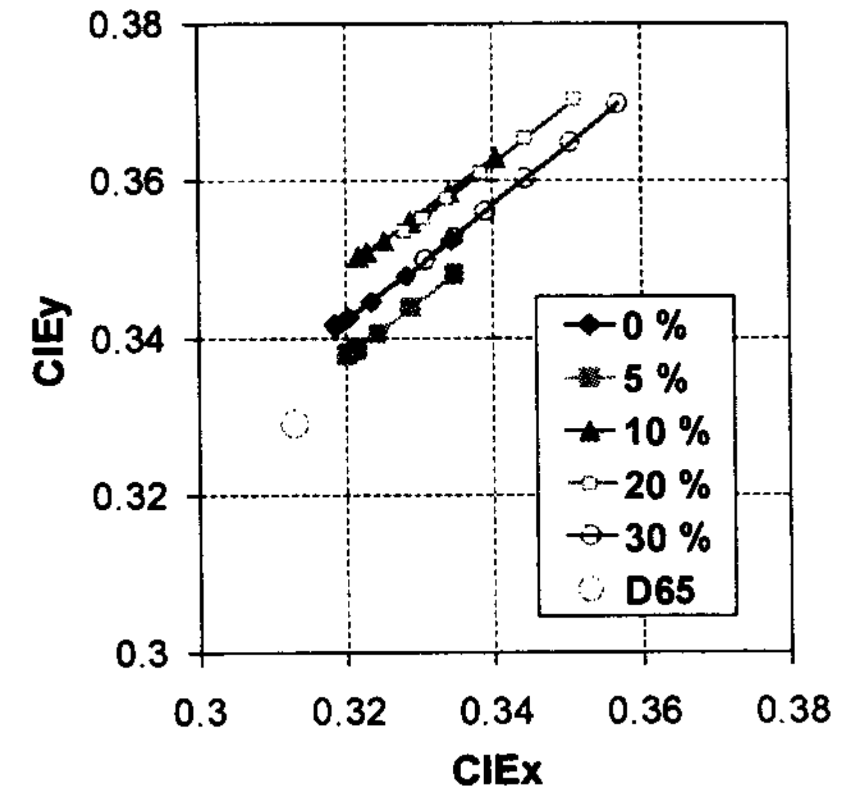

Figure 5. Effect of yellow assist dopant concentration in on chromaticity as a function of current density.

Figure 6 shows the luminance efficiency as a function of current density for an optimized white emitting OLED at two concentrations of blue layer assist dopant. For this configuration, the optimum blue assist dopant concentration is in the range of 7-10%, and is chosen based on the combination of the target white point, luminous efficiency and chromaticity change with current density. In order to minimize the effects on color balance and gray scale for the RGB and RGBW formats, it is important that the efficiency and the chromaticity of the white OLED does not change as the current density varies. Both the yellow and blue assist dopant concentrations have been found to be important in this regard.

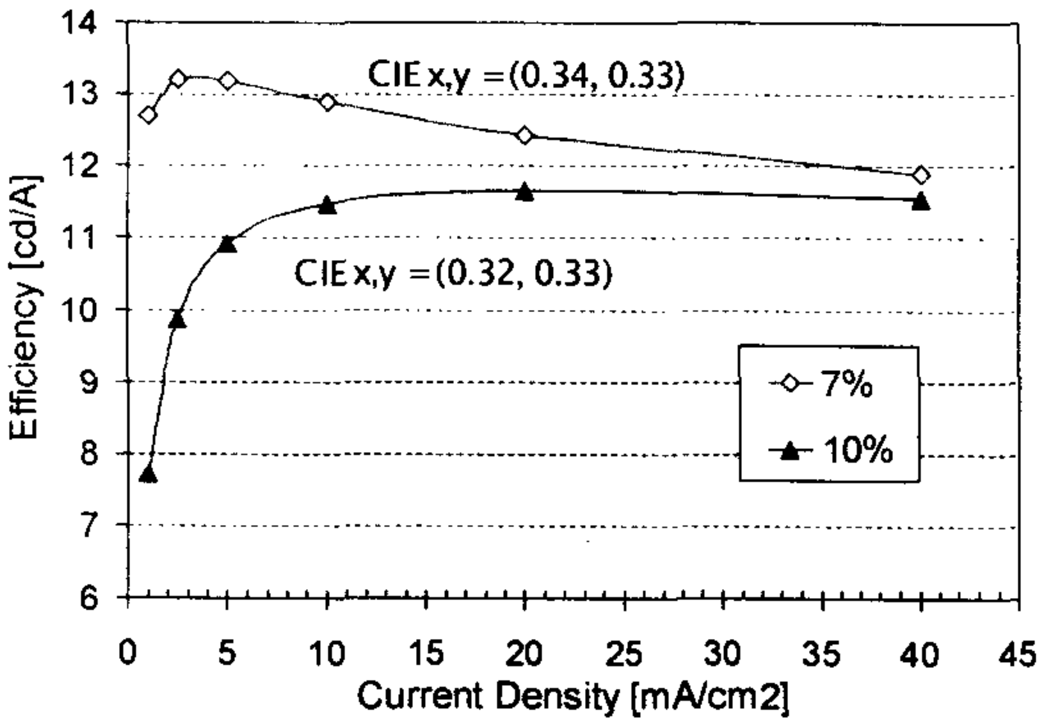

Figure 6. Effect of assist dopant concentration in the blue layer on luminance efficiency as a function of current density.

In order to evaluate the performance of the various white formulations in a display, a model was developed that uses the white efficiency and spectral characteristics as inputs. The power consumption was calculated for both RGB and RGBW display formats with color configurations illustrated in Figure 7 for 2.16" diagonal displays (14.4 cm^2) using typical LCD color filters and a circular polarizer with a transmittance of 44%. The power consumption is the average power consumption required for a set of 13,000 digital camera images at a display luminance (maximum) of 180 cd/m^2. The target color temperature was 6500 K. Further details of the calculation are described elsewhere (see paper in this proceedings by Arnold et al. entitled "Full Color AMOLED with RGBW Pixel Pattern").

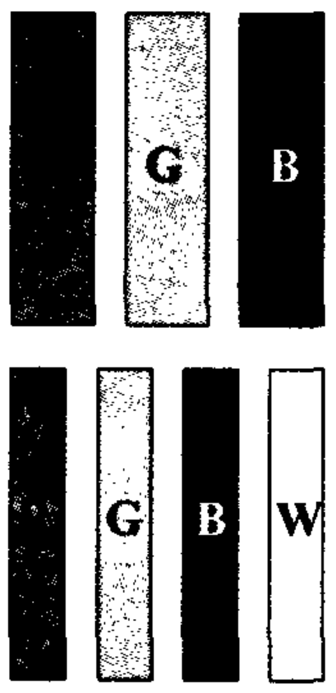

Figure 7. RGB and RGBW pixel configuration.

Table 1 gives the luminance and chromaticity of the white OLED as well as the corresponding calculated average power consumptions, for both the RGB and RGBW display formats.

Device No.	Luminance Efficiency (cd/A)	CIEx	CIEy	RGB Power Consumption (mW)	RGBW Power Consumption (mW)
1	10.6	0.29	0.29	623	318
2	12.1	0.34	0.32	537	262
3	12.9	0.36	0.33	514	283
4	14.4	0.38	0.36	517	306
5	15.7	0.40	0.38	532	356
6	15.6	0.43	0.40	648	499

Table 1. Dependence of the power consumption on the efficiency and color of the unfiltered white OLED for 2.16" diagonal RGB and RGBW displays. Filter set "A" was used for the power consumption calculations.

It is evident that the RGBW format requires approximately one-half the power of the RGB format. The reason for this is that highly saturated colors comprise only a small portion of most images and a large fraction of the pixel emission can be provided by unfiltered white emission. The power consumption for a particular white formulation also depends on the hue of the unfiltered white sub pixel. The lowest power consumption was obtained when the white sub pixel was closest to the D65 point (CIE x = 0.313, CIE y = 0.329). For white emission far from the target D65 point, such as Device #6 in Table 1, significant emission from a filtered sub-pixel (in this case the blue sub-pixel) is required, which results in higher power consumption.

Table 2 shows the efficiency and chromaticity coordinates of the R, G, and B filtered emission for Device #2 in Table 1. Two sets of color filters were used in the simulation, set A optimized for power consumption and set B optimized for color gamut. It is clear that the filter type influences the color and efficiency of the display and the appropriate filter selection will depend on the target display application.

Filter Set	Luminance Efficiency (cd/A) @20 mA/cm2	Color (CIEx, CIEy)
None	12.1	0.34, 0.32
Red A	3.6	0.60, 0.35
Green A	7.3	0.35, 0.50
Blue A	1.9	0.13, 0.13
Red B	2.6	0.64, 0.36
Green B	6.2	0.32, 0.55
Blue B	1.2	0.12, 0.10

Table 2. Primary colors obtained with white OLEDs and two different sets of color filters.

The white OLEDs described in this paper have excellent operational stability under accelerated operating conditions. Figure 8 shows the luminance decay curves for Device # 2 with starting luminance level of 635. 1250. 2420 and 9.300 cd/m^2 at current densities of 5, 10, 20 and 80 mA/cm^2 respectively. The extrapolated half-life at room temperature for operation at constant current, with an initial luminance of 2.420 cd/m^2 is expected to be greater than 5.000 hours. and with an initial luminance of 1250 cd/m2 is expected to be greater than 15.000 hours.

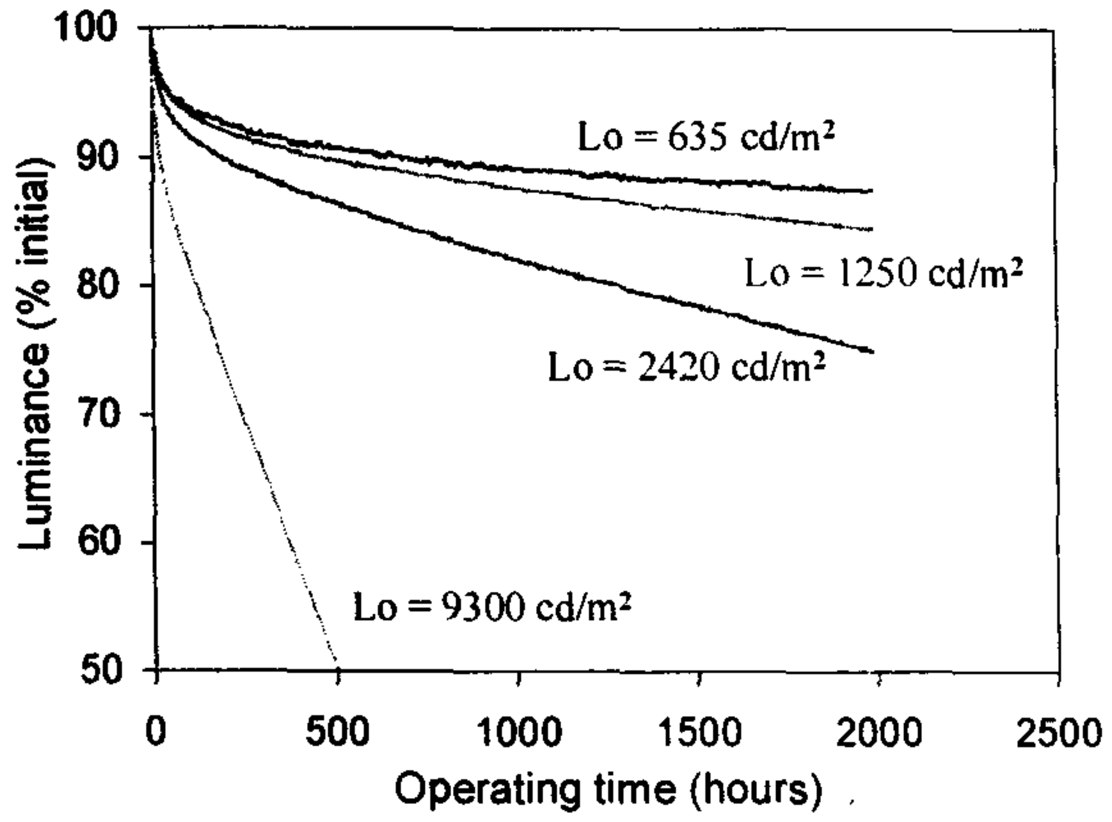

Figure 8. Operational stability.

We also found that the spectral emission was relatively unaffected during operational stability testing. with a maximum chromaticity change of about 0.02 units observed for the device tested at 80 mA/cm^2 after 500 hours of continuous operation. It is expected that the chromaticity change for the devices tested at lower current density will be approximately the same when the 50% initial luminance level is reached for these conditions.

3. Conclusions

Optimized white OLED structures enable the fabrication of full color displays in both the RGB and RGBW formats. These structures have high efficiency, long operational lifetime and spectra that are largely insensitive to current density. Optimization of the white emitter is important to minimize the power consumption of RGB and RGBW displays. with the lowest power consumption obtained when the white sub pixel chromaticity is closest to the D65 point. The RGBW format. which utilizes a high-efficiency unfiltered white sub-pixel. results in one-half the power consumption of the analogous RGB format.

4. References

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