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Comparative study of single and multiemissive layers in inverted white organic light-emitting devices

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The authors have fabricated and compared highly efficient inverted white organic light-emitting devices (WOLEDs) with a single emission layer (SEL) and with a multiemission layer (MEL). The efficiency levels of the WOLEDs with a SEL and a MEL achieved 13.0 cd/A, 10.6 lm/W and 11.3 cd/A, 7.3 lm/W, respectively. The projected half lifetime of a SEL device under an initial luminance of 400 cd/m^2 is expected to be over 34 000 h, which is five times better than that of a MEL device of 6350 h. The Commission International de l'Eclairage coordinates of a SEL device are not affected by aging. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2348089]

Recently, white organic light-emitting devices (WOLEDs) have gained a great deal of attention due to their potential applications in the fabrication of full-color displays with color filters, and of backlights for liquid-crystal displays. Currently, there are two major methodologies for achieving white emission from OLEDs, one is to construct the red-green-blue primaries or their complimentary colors from their respective layers of a multiemitting layer (MEL) structure[1–5] and the other is to use a single emission layer (SEL) with mixed emissive colors.[6–10] From the outset, the SEL WOLED is simpler than the MEL WOLED, but the control of various dopant concentrations within the emissive layer can be very critical. It usually requires very low doping concentration and the color emission can be very sensitive to the doping concentration. Previously, the MEL device has been shown to be more efficient than that of a SEL device; however, the MEL device is difficult to control and optimize due to the fact that the composed white emission spectrum is sensitive not only to doping concentrations but also to the applied voltage as well as layer thicknesses. This is because the emission of a MEL WOLED is derived from at least two different carrier recombination zones (RZs). Therefore, the variation of Commission International de l'Eclairage (CIE) coordinates is dependent upon the drive voltage change which is intimately related to the shift of RZs within the emissive layers. Recently, Choi *et al.*[11] reported that the MEL WOLED emission spectrum is independent of voltage and could be attributed to the narrowing effect of the width of the RZs. However, the more important issue of variation of the CIE coordinate of a WOLED with the elapse of driving time in order to maintain a constant driving current density has not been addressed.

We have reported the development of highly efficient inverted bottom-emission OLED,[12,13] which can be integrated readily with the *n* channel of the amorphous Si thin film transistor backplane for future large-size active matrix OLED. In this letter, two types of inverted WOLED with either SEL or MEL have been fabricated and compared. We find that the efficiency of an inverted WOLED with SEL and MEL is all very high. Furthermore, the CIE coordinate variations are both less than 0.02 between luminance levels of 200 and 10 000 cd/m^2, respectively. However, the white emission spectrum of the MEL device significantly changes to off-white after a period of driving at a constant current density. In contrast, the SEL WOLED displays a comparatively higher level of stability with a slower rate of luminance decline, and its CIE coordinates were independent of operative aging. The SEL WOLED showed a higher efficiency (13 cd/A) than that of MEL WOLED (11.3 cd/A). In addition, at the initial luminance of 400 cd/m^2, the projected half lifetime of a SEL device is five times greater than that of a MEL device.

The configuration of and fabrication materials used in the WOLED devices are shown in Fig. 1. The devices were prepared using the conventional method of vacuum deposition onto a cleaned indium tin oxide (ITO) glass substrate. In the first stage, the electron injection layers of Mg (Ref. 12) and Cs_2O:Bphen (Ref. 13) were deposited onto the ITO bottom cathode. Next, a layer of tris(8-

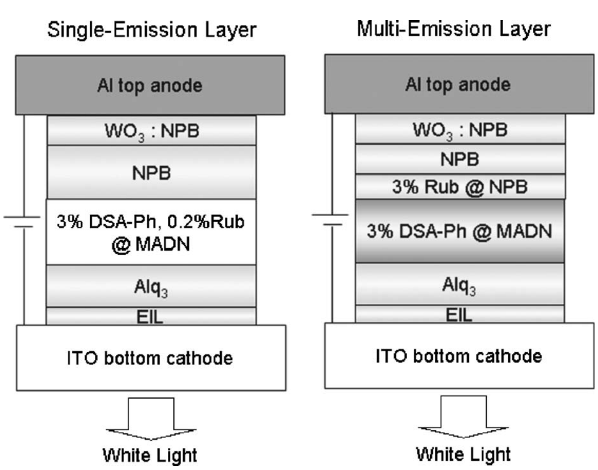

FIG. 1. Configuration of SEL and MEL devices.

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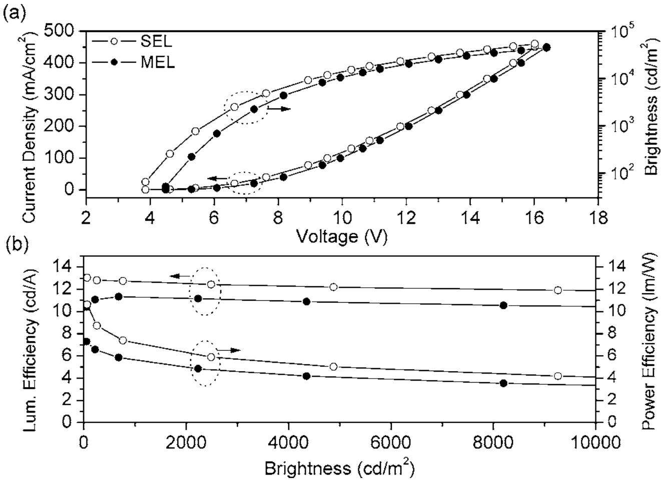

FIG. 2. (a) Current density-voltage-brightness (*J-V-L*) and (b) luminance efficiency-brightness-power efficiency (*L-B-W*) characteristics for WOLEDs with SEL and MEL.

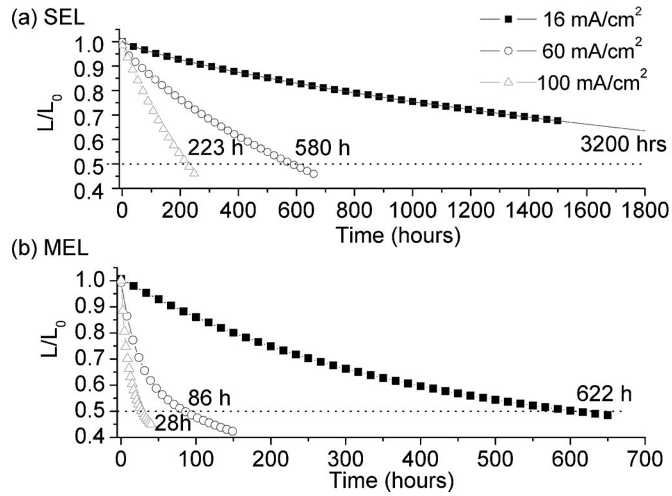

FIG. 3. Stabilities of (a) SEL devices and (b) MEL devices measured at current densities of 16, 60, and 100 mA/cm^2.

hydroxyquinolinato)aluminum (III) (Alq_3) was used as the electron transport layer. Then, the emitting layer composed of the *p*-bis(*p*-*N*,*N*-di-phenyl-aminostyryl)benzene[14] (DSA-Ph) blue dopant and 5,6,11,12-tetra(phenyl)naphthacene (rubrene) yellow dopant was evaporated with a host material of 2-methyl-9,10-di(2-naphthyl) anthracene[15] (MADN) in a single emission layer. Another feature of this stage involves the MEL which is comprised of a DSA-Ph doped into a MADN of blue emission layer and rubrene doped into a *N*, *N′*bis(1-naphthyl)-*N*, *N′*bis(phenyl)benzidine (NPB) of yellow emission layer. Next, the NPB as the hole transport layer was evaporated followed by the WO_3 and NPB which were evaporated as the hole injection layer.[16] Finally, the devices were completed by the anode deposition of Al. The structure of the SEL device is ITO/Mg (1 nm)/Cs_2O:Bphen (11 nm)/Alq_3 (15 nm)/3% DSA-Ph:MADN:0.2% rubrene (40 nm)/NPB (55 nm)/WO_3:NPB (10 nm)/Al, and the structure of the MEL device is ITO/Mg(1 nm)/Cs_2O:Bphen (11 nm)/Alq_3 (15 nm)/3% DSA-Ph:MADN (40 nm)/3% rubrene:NPB (20 nm)/NPB (35 nm)/WO_3:NPB (10 nm)/Al. The current density-voltage-luminance (*J-V-L*) characteristics of devices used a diode array rapid scanning system that included a Photo Research PR650 spectrophotometer and a computer controlled programmable dc source.

Figure 2 shows the maximum current and power efficiency of a SEL device which are 13.0 cd/A and 10.6 lm/W, respectively. By contrast, a MEL device has a current efficiency of 11.3 cd/A and a power efficiency of 7.3 lm/W. Furthermore, with a current density of 20 mA/cm^2, the brightness and external quantum efficiency achieved by a SEL device are 2490 cd/m^2 and 4.6% and by a MEL device are 2230 cd/m^2 and 4.0%, respectively. The SEL device has a lower voltage of 6.6 V when compared with that of a MEL device which is 7.2 V at 20 mA/cm^2. This is because the mobility of NPB is reduced when the rubrene is doped into the NPB of a MEL. The optimized dopant concentration of rubrene that produced a white emission was 0.2% in SEL and 3% in MEL, respectively. Considering the fact that the application of a conventional display requires a level of brightness between 200 and 10 000 cd/m^2, the observed change of CIE chromaticity from (0.31, 0.44) to (0.29, 0.42) for a SEL device and (0.36, 0.45) to (0.34, 0.43) for a MEL being less than 0.02 is very positive. The CIE coordinates are independent of the current density in a SEL WOLED due to its single exciton recombination zone. However, the bias-dependent color variation has been attributed to a shifting of the recombination zone in a MEL at different current densities which is itself a result of the variable levels of mobility involving the hole and the electron carrier. We found that our MEL WOLED has only a small variation in the CIE coordinates that is similar to the SEL WOLED device. This might be attributed to the fact that the hole and electron are more balanced in the inverted structure disclosed in this letter. It has been observed that the current densities of electron injection and hole injection have increased with bias almost equally. Therefore, we conclude that in our MEL device the recombination zone has not shifted significantly and the CIE coordinates have changed only slightly.

Figure 3 shows the operational stabilities of two types of inverted WOLED which have been monitored in a nitrogen glovebox under constant current densities at 16, 60, and 100 mA/cm^2, respectively. The half lifetimes of the SEL devices of 580 and 223 h have been obtained in a real situation at high current densities of 60 and 100 mA/cm^2, respectively. These half-lifetime measurements are longer than

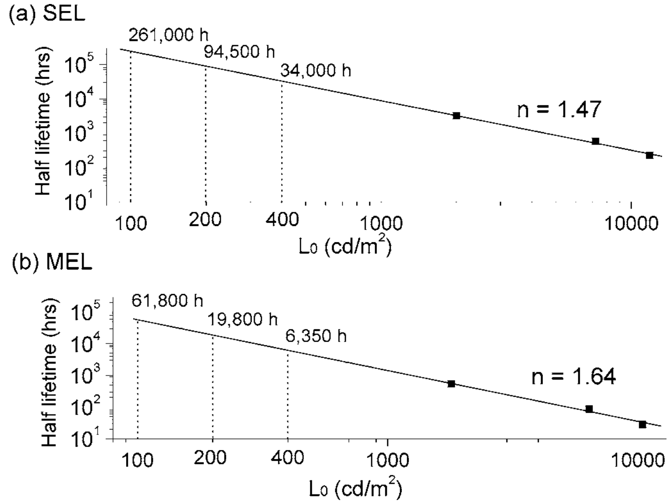

FIG. 4. Extrapolated half life of WOLEDs with SEL and MEL.

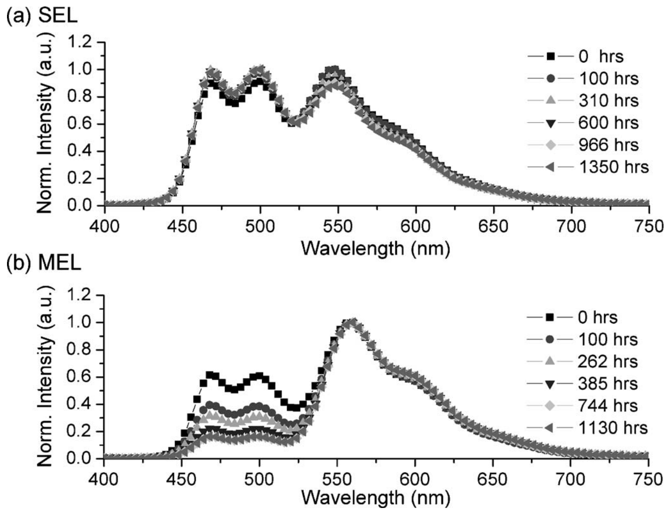

FIG. 5. $CIE_{x,y}$ coordinates of (a) SEL device and (b) MEL device measured at a constant current density of 16 mA/cm^2.

those of the MEL devices which are only 86 and 28 h, respectively. The initial luminances of a SEL device and a MEL device are 2000 and 1800 cd/m^2, respectively, at 16 mA/cm^2. The extended line of measurement at 16 mA/cm^2 was fitted using a stretched exponential decay (SED).[17] It was found that the extrapolated half lifetime of the SED device is 3200 h and this is much longer than that of a MEL device with 622 h. In order to determine whether or not the half lifetime is suitable for use in display luminance, the lifetime was extrapolated according to the following formula:

$$L_0^n \times T_{1/2} = \text{const},$$

where $T_{1/2}$ is the time needed for the luminance to decrease to 50% of the initial value and n is an acceleration exponent. The experimentally fitted acceleration factors of n for both SEL and MEL devices are 1.47 and 1.64, respectively. The half lifetimes of SEL and MEL are projected to be 261 000 and 61 800 h, respectively, at an initial luminance of 100 cd/m^2 (as shown in Fig. 4). As commercial WOLEDs require a much higher brightness of 400 cd/m^2, the half lifetime of a SEL device is still over 34 000 h, which is five times longer than that of a MEL device of 6350 h. More importantly, it was found that the CIE coordinates of a SEL device are independent of driving time. Consequently, with a slight variation (0.014, 0.015) in the CIE coordinates, the color stay in white emission after continuous driving for a period of 1350 h experiences a 31% luminance decay from an initial luminance of 2000 cd/m^2 (as shown in Fig. 5). However, after a significant CIE coordinates variation of (0.032, 0.019), it was observed that the MEL device experienced a 13% decay in luminance decay from an initial luminance of 1800 cd/m^2 after only 100 h of operation. In addition, the color changed from white emission at $CIE_{x,y}$ (0.36, 0.45) to yellow emission at $CIE_{x,y}$ (0.41, 0.47) after 262 h (31% of luminance decay) and finally to $CIE_{x,y}$ (0.44, 0.49) after 744 h with continued enhancement of yellow emission.

Although the CIE coordinates of both types of inverted WOLED have only a small deviation in brightness between 200 and 10 000 cd/m^2, the $CIE_{x,y}$ of the MEL WOLED changed quickly due to a decrease in the blue emission during driving. The result can be explained by the increased barrier height between the organic and the electrodes during driving and by the potential morphological change of the organic materials created by thermal stress which in turn brings about a slight shift of the recombination zone. The recombination zone of the MEL device slightly shifts towards the yellow emission layer causing the color to change significantly during driving. However, the SEL device which has only one exciton recombination layer also experiences a slight shift in the recombination zone, but the emissive color continues to be derived from the same single emission layer. Even though there is a slight decrease in luminance during driving involving the SEL device, the color emission remains to be white.

In conclusion, we have fabricated highly efficient inverted WOLEDs with both SEL and MEL devices. The maximum current efficiency and power efficiency of a SEL device are 13 cd/A and 10.6 lm/W, respectively. By contrast, a MEL device has a current efficiency of 11.3 cd/A and a power efficiency of 7.3 lm/W. The $CIE_{x,y}$ coordinate variations for both are less than 0.02 between luminance levels of 200 and 10 000 cd/m^2, respectively. The projected half lifetime of a SEL device under the initial luminance of 400 cd/m^2 is over 34 000 h, which is five times better than that of a MEL device with only 6350 h. Finally, it was noted that the CIE coordinates of a SEL device are independent of driving, while the MEL device was observed to experience a significant color change, from white to yellow emission, during the same driving.

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