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Angle-stable top-emitting white organic light-emitting devices employing a down-conversion layer

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ABSTRACT

Angle-stable white top-emitting organic light-emitting devices (WTEOLEDs) by the combination of a blue TEOLED with a down-conversion (DC) layer are demonstrated. The DC layer is composed of red fluorescent dye doped in a host of tris (8-hydroxy-quinolinato) aluminum. The TEWOLED shows a CIE coordinates of (0.240, 0.332) and a maximum current efficiency of 3.95 cd/A. Furthermore, the WTEOLED shows excellently angle-stable characteristic, the CIE coordinates at 20 mA/cm^2 only shift by (0.023, −0.007) from 0° to 60°. It can be attributed to the angle-stable blue TEOLED based on the Ag/Ge/Ag transparent cathode.

Researches on organic light-emitting devices (OLEDs) in recently years have proved the huge potential of OLED for full-color display and solid-state lighting [1–4]. Generally, white OLEDs (WOLEDs) can be obtained by employing two or more different complementary colors emitters in the emitting layer [5–8]. However, because of the difference of aging rate for different emitting materials and the shifting of recombination region, spectra of such WOLEDs will change considerably as operation times and driving voltages increasing. To solve the problems, the down-conversion (DC) concept, where a blue emitter can be combined with its complementary photoluminescence (PL) to produce the white light, have been proposed to fabricate the WOLEDs [9]. Employing the DC layers, the bottom emitting WOLEDs (WBOLED) have been reported with the apparent advantages of high color stability, simple device structure and easy fabrication process [10–13]. Moreover, based on the DC system, Krummacher et al. report an excellent WBOLED, efficiency of which can attain to 25 lm/W [14].

Top-emitting OLEDs (TEOLEDs) are suited for high-aperture-ratio displays as they can be fabricated on opaque backplane. And TEOLEDs can be deposited onto arbitrary substrates (such as flexible substrate) which will help to expand the application scope of the OLEDs. However, as a result of the strong microcavity, narrowed and angle-dependent spectra challenge the researches on top-emitting white OLEDs (TEWOLEDs). Recently, the TEWOLEDs adopting DC layers have been demonstrated as an effective method for produce white light. The TEWOLEDs based on down-conversion phosphors are demonstrated by Ji et al. firstly, with the Commission Internationale de L'Eclairage (CIE) coordinates of (0.218, 0.279) and an efficiency of 1.1 cd/A [15]. Chen et al. reported the TEWOLEDs based on aggregation-induced-emission DC layer exhibit high efficiency (17.7 cd/A) [16]. By employing a heterostructure of DC layers, Leo et al. fabricated the TEWOLEDs with an improved color rendering index of 60, a better control of CIE coordinates, and an efficiency of 1.4 cd/A [17]. Nevertheless, these devices still have the great challenge in obtaining angle-stable emission spectra due to the strong microcavity in the blue TEOLEDs. In this work, we fabricate the TEWOLEDs with DC layer by using the Ag (15 nm)/Ge (5 nm)/Ag (5 nm) (AGA) cathode which has been demonstrated as an efficient transparent cathode for angle-stable TEOLEDs [18,19]. Based on AGA transparent cathode, the TEWOLEDs exhibit considerably high stability as either driving voltage or viewing angle.

All devices are evaporated by thermal evaporating on the pre-cleaned glass substrates under the high vacuum (~5×10^{-4} Pa). The deposition rates for all materials are in the range of 0.2–1.0 Å/s and thicknesses are measured with quartz crystals. Luminance-current-voltage characteristics of unpackaged devices are measured simultaneously using a Keithley 2400 Source Meter and a Minolta Luminance Meter LS-110 in air at room temperature. The electroluminescence (EL) spectra of the devices are measured with Ocean Optics Maya 2000-PRO spectrometer. Absorption (abs.) and photoluminescence (PL) spectra are measured with a Shimadzua UV-3101PC spectrophotometer and Hitachi F-4500 fluorescence spectrophotometer.

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The blue TEOLED is composed of glass substrate/Ag (100 nm)/MoO_3 (3 nm)/Di-[4-(*N*,*N*-ditolyl-amino)-phenyl] cyclohexane (TAPC) (25 nm)/4,4′,4″-tris(carbazol-9-yl)-triphenylamine (TCTA) (5 nm)/Emission Layer (EML) (30 nm)/4,7-Diphenyl-1,10-phenanthroline (Bphen) (30 nm)/8-Hydroxy-quinolinolato-lithium (Liq) (2 nm)/Ag (15 nm)/Ge (5 nm)/Ag (5 nm)/Tris(8-hydroxy- quinolinato)aluminum(Alq_3, 40 nm), where the Alq_3 is the light out-coupling layer. The emission layers of the monochromic device is formed with a bipolar host 2,7-bis (diphenylphosphoryl)-9-[4-(N,N-dipheny-lamino)phenyl]-9-phenylfluorene (POAPF) doped with 8wt % bis(3,5-difluoro-2-(2-pyridyl)phenyl-(2-carboxypyridyl) iridium(III) (Firpic). The DC layers in this work are formed by the deep red emitter diphenylamino (PhsPDCV) doped in Alq_3 at 50 wt%. The fluorescence quantum yield of the PhsPDCV solid film is about 33% [20]. The schematic layer structures of the fabricated devices A, B, and C are shown in Fig. 1.

The absorption and PL spectra of the DC materials, and the EL spectra of Firpic are shown in Fig. 2. The EL spectra of Firpic exhibit a peak at 475 nm with the shoulder at ~500 nm. It can be seen clearly that PhsPDCV has a high absorption at the EL spectra peak (475 nm) of Firpic; and that, there is less superposition between the absorption of Alq_3 and EL spectra of Firpic. Alq_3 and PhsPDCV have strong PL emission in the green (513 nm) and in the deep red region (643 nm) (in web version), respectively. In the system of Alq_3:PhsPDCV, emission spectra of Alq_3 overlap quite well with the absorption of PhsPDCV, which indicates that a complete energy−transfer from Alq_3 to PhsPDCV can be anticipated. Besides, Alq_3 also acts as a spacer for PhsPDCV to prevent the quenching of the emission.

Fig. 3 shows the normalized EL spectra of devices with different DC layer thicknesses, and the inset is the relative EL spectra for the blue device and white device at the same current density of 20 mA/cm^2. Except the peak of 475 nm from the blue TEOLEDs, the spectra of devices B and C also have peaks at 643 nm which arise from the PL emission of DC layers. Besides, as the thickness of the DC layer increases, the emission intensity at 500−550 nm are enhanced which should be related to the light-coupling effect of the additional DC layer. The unabsorbed blue emission and the red PL emission of device C yield a cold white emission with the CIE coordinates of (0.240, 0.332). Additionally, though the integral calculation based on the relative EL intensity of the spectra shown in the inset of Fig. 3 and 76% of the emission for Firpic is absorbed by the DC layer, and only about 12.2% of the absorbed part is converted to the red PL emission. The normalized EL spectra of white

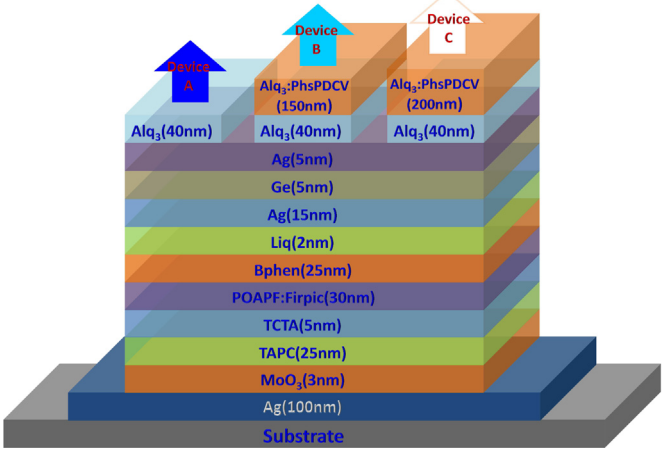

Fig. 1. Schematic layer structures of the fabricated devices with different DC layers.

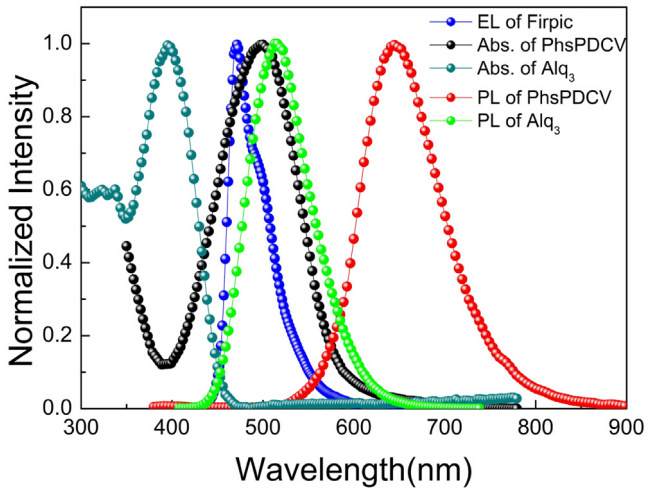

Fig. 2. Abs. and PL spectra of the DC materials, and the EL spectra of Firpic.

device C under different voltages are shown in Fig. 4. As the driving voltage increases from 4 V to 7 V, no visible EL spectra variation can be observed, which indicates that the device presents relatively color stability. The emission intensity of the DC material PhsPDCV depends on that of Firpic directly, resulting that the spectra ratio between blue and red emission will remain the same. Thus, as the driving voltage increases, the EL emission intensity of Firpic will be enhanced, but spectra of the device will not change.

The AGA has been demonstrated as an efficient transparent cathode for angle-stable TEOLEDs since the low-reflectivity AGA transparent cathode forms less angle-dependent cavity emission in the devices. Fig. 5(a) shows the normalized EL spectra of the blue TEOLEDs based on AGA cathode under different viewing angles at 20 mA/cm^2. It can be clearly seen that the CIE coordinates of the blue device change only from (0.132, 0.275) at 0° to (0.131, 0.249) at 60°, which indicates that the blue device processes the relatively stable angle characteristic. The EL spectra of the white device with the 200 nm DC layer also exhibit fairly stable under different angles, as shown in Fig. 5(b). The CIE coordinates of white device at 20 mA/cm^2

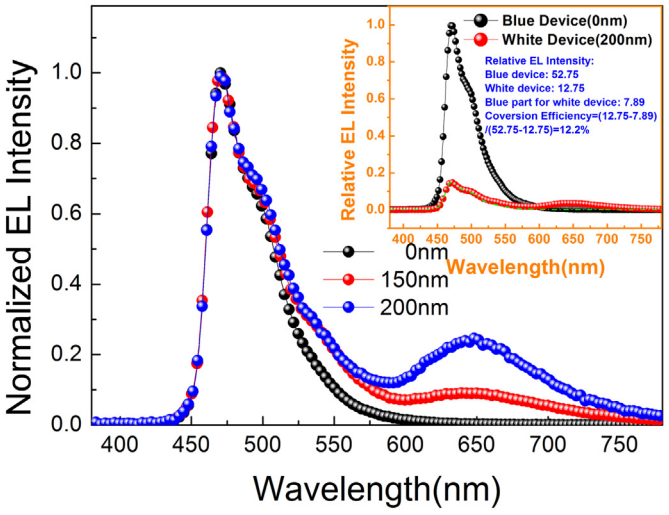

Fig. 3. Normalized EL spectra for the devices with different DC layers. The inset is the relative EL spectra for the blue device and white device at the same current density of 20 mA/cm^2.