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## White organic light-emitting devices with a bipolar transport layer between blue fluorescent and orange phosphorescent emitting layers

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White organic light-emitting devices based on an orange phosphorescent iridium complex, bis(2-(2-fluorophenyl)-1,3-benzothiazolato-*N*,*C*<sup>2'</sup>) iridium (acetylacetonate) [(F-BT)<sub>2</sub>Ir(acac)] and blue fluorescent 4,4'-bis(2,2'-diphenylvinyl)-1,1'-biphenyl are reported. By introducing a bipolar transport 4,4'-*N,N'*-dicarbazole-biphenyl layer between the fluorescent and the phosphorescent emission layers, additional light emission from (F-BT)<sub>2</sub>Ir(acac) is observed. The authors attributed it to the elimination of the Dexter energy transfer between the two emitters. Pure white emission with Commission Internationale de l'Eclairage coordinates of (0.33, 0.34) and a maximum luminance of 40960 cd/m<sup>2</sup> were obtained. The maximum current efficiency and the color rendering index of the device are 13.4 cd/A and 71, respectively. © 2007 American Institute of Physics. [DOI: 10.1063/1.2757096]

White organic light-emitting devices (WOLEDs) have attracted more and more attention because of their potential use in backlight, full color applications, as well as in lighting purposes.<sup>1</sup> In order to generate the desired white light, WOLEDs with various configurations have been proposed, such as using multiple emission layers in which each layer emits a different color light to generate white-light emission,<sup>2-9</sup> using single emission layer with multiple dyes,<sup>10,11</sup> using excimer or exciplex emission,<sup>12-14</sup> using microcavity structure,<sup>15</sup> and so on. Among these approaches, WOLEDs employing phosphorescent materials are most effective because phosphorescent materials can harvest both singlet and triplet excitons which lead to the potential for achieving 100% internal quantum efficiency.<sup>16,17</sup> But the instability and the low efficiency of the blue phosphorescent dyes, as well as their demand for wide band-gap host materials, will hamper their application in field of display or lighting. In general, the emission spectra of organic materials are broader than that of inorganic materials, thus two complementary colors can produce white-light emission. So the combined use of blue fluorescent and orange phosphorescent dyes may solve these problems and obtain efficient and stable WOLEDs.<sup>18-20</sup> Recently, Schwartz *et al.*<sup>18</sup> have demonstrated efficient WOLEDs based on blue fluorescent and orange phosphorescent materials by introducing a bipolar interlayer of coevaporated 4,4',4''-tris(*N*-carbazolyl)-triphenylamine and 2,2',2''-(1,3,5-benzenetriyl) tris-[1-phenyl-1*H*benzimidazole] to suppress energy transfer between the two emitters.

Here we reported an efficient WOLED by introducing a bipolar transport 4,4'-*N,N'*-dicarbazole-biphenyl (CBP) layer between blue fluorescent and orange phosphorescent layers. Dexter energy transfer between the two layers is

eliminated, which improves the device performances. Furthermore, emission color can also be tuned by changing the interlayer thickness.

The structure of the device consists of indium tin oxide (ITO)/4,4',4''-tris(3-methylphenylphenylamino)-triphenylamine (m-MTDATA: 30 nm)/*N,N'*-bis-(1-naphthyl)-*N,N'*-diphenyl-1,1'-biphenyl-4,4'-diamine (NPB: 20 nm)/4,4'-bis(2,28-diphenylvinyl)-1,1'-biphenyl (DPVBi: 15 nm)/CBP (*x* nm)/CBP: 8% (F-BT)<sub>2</sub>Ir(acac)] (8 nm)/2,9-dimethyl-4,7-diphenyl-1,10-phenanthroline (BCP: 10 nm)/tri(8-hydroxyquinoline) aluminum (Alq<sub>3</sub>:30 nm)/LiF (0.8 nm)/Al [*x*=0, 2, 5, and 8 nm for devices A, B, C, and D, respectively. [(F-BT)<sub>2</sub>Ir(acac) stands for bis(2-(2-fluorophenyl)-1,3-benzothiazolato-*N*,*C*<sup>2'</sup>) iridium (acetylacetonate)<sup>21</sup>]. And the energy level diagram of the device is inserted in Fig. 1. m-MTDATA, NPB, DPVBi, CBP doped with (F-BT)<sub>2</sub>Ir(acac), BCP, Alq<sub>3</sub> were used as hole-injection layer, hole-transporting layer (HTL), blue fluorescent layer, orange phosphorescent layer, hole-blocking layer (HBL), and electron-transporting layer, respectively. An undoped CBP layer is introduced to separate blue and orange emitting layers. Prior to the device fabrication, ITO-coated glass substrates were carefully cleaned by scrubbing and sonication. All organic layers were deposited onto the substrate in high vacuum (10<sup>-6</sup> Torr) by thermal evaporation with a rate of 0.1–0.2 nm/s. Then, a bilayer cathode of LiF/Al was subsequently vapor deposited onto the organic films. The layer thickness and the deposition rate of the materials were monitored *in situ* using an oscillating quartz thickness monitor. The electroluminescent (EL) spectra and Commission Internationale de l'Eclairage (CIE) coordinates of the devices were measured by using a PR650 spectroscan spectrometer. The luminance-voltage and current-voltage characteristics were measured simultaneously with a programmable Keithley 2400 voltage-current source. All measure-

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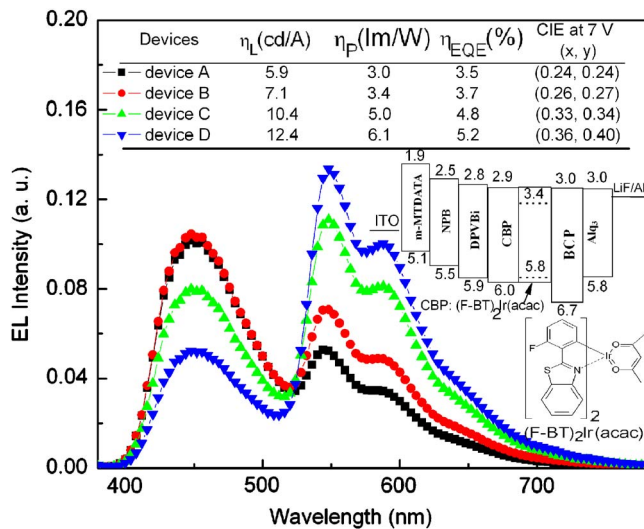


FIG. 1. (Color online) Non-normalized EL spectra of the devices A–D at a current density of 75 mA/cm<sup>2</sup>. The inset shows the performance of devices A–D, the chemical structure of (F-BT)<sub>2</sub>Ir(acac), and the energy level diagram of the device. ( $\eta_L$ : maximum current efficiency,  $\eta_p$ : maximum power efficiency,  $\eta_{EQE}$ : maximum external quantum efficiency)

ments were carried out at room temperature under ambient conditions.

Figure 1 shows the non-normalized EL spectra of the devices A–D at a current density of 75 mA/cm<sup>2</sup>. The spectra of the devices show two main peaks at 448 and 548 nm originating from DPVBi and (F-BT)<sub>2</sub>Ir(acac). As can be seen, the emission intensity of (F-BT)<sub>2</sub>Ir(acac) increases with minor change in the intensity of the emission from DPVBi when  $x$  changes from 0 to 2 nm. The additional emission of (F-BT)<sub>2</sub>Ir(acac) could be attributed to the elimination of Dexter energy transfer between these two emitters. The triplet energy level of (F-BT)<sub>2</sub>Ir(acac) is higher than that of DPVBi, when DPVBi layer is adjacent to CBP: 8% (F-BT)<sub>2</sub>Ir(acac) layer ( $x=0$  nm), Dexter energy transfer from the phosphor triplet state of (F-BT)<sub>2</sub>Ir(acac) to the lower nonradiative triplet state of DPVBi can occur, which reduces the emission from (F-BT)<sub>2</sub>Ir(acac). When 2 nm undoped CBP is introduced between DPVBi and the orange phosphorescent emission layer, Dexter energy transfer is

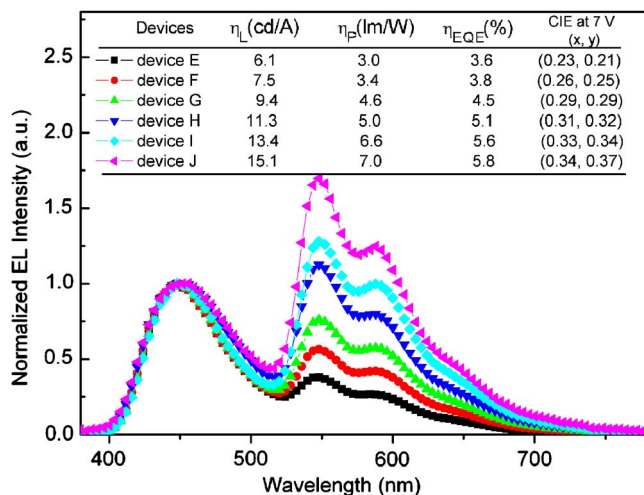


FIG. 2. (Color online) Normalized EL spectra of devices E–J at 7 V. The inset shows the performance of devices E–J.

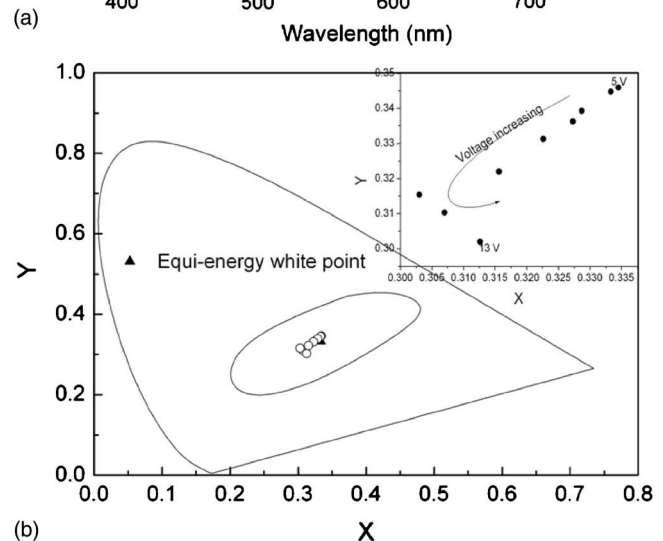
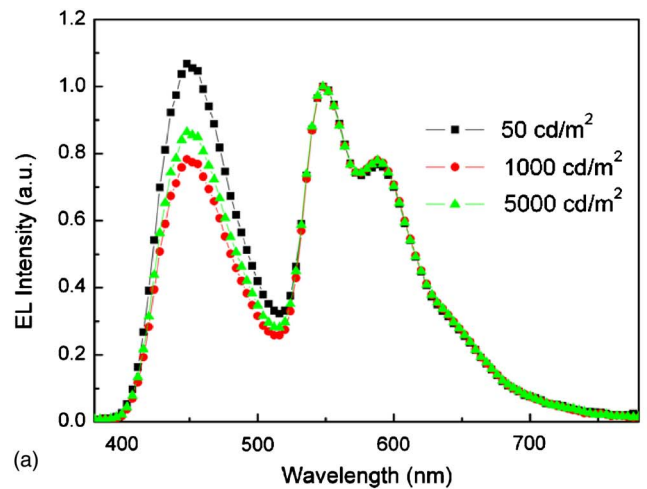


FIG. 3. (Color online) (a) Normalized EL spectra at different luminances and (b) CIE coordinates of device I at different voltages. The arrow indicates increasing voltages from 5 to 13 V.

prevented because it can only occur within 1–2 nm,<sup>18</sup> which enhance the emission of (F-BT)<sub>2</sub>Ir(acac). Note that when the thickness of CBP increases from 2 to 8 nm, the intensity of the emission of (F-BT)<sub>2</sub>Ir(acac) increases, while that of DPVBi decreases. The phenomena can be attributed to the change of exciton recombination zone. At the same current density, the number of the charge carriers is constant. Excitons are generated at both HTL/DPVBi and CBP: 8% (F-BT)<sub>2</sub>Ir(acac)/HBL interfaces. As the thickness of the undoped CBP layer increases, the number of the electrons reaching the HTL/DPVBi interface is reduced because CBP shows preferred transport properties for holes. Thus, fewer excitons are generated at HTL/DPVBi interface and the emission of DPVBi decreases. While relatively more excitons are generated at CBP: 8% (F-BT)<sub>2</sub>Ir(acac)/HBL interface, which leads to the stronger emission of (F-BT)<sub>2</sub>Ir(acac).

The inset in Fig. 1 is the chromaticity and efficiency values of the devices A–D. The external quantum efficiency of the devices is calculated utilizing the method presented by Okamoto *et al.*<sup>22</sup> The maximum efficiency of device B is 7.1 cd/A, which is higher than that of device A (5.9 cd/A). The improved efficiency is attributed to introduction of CBP layer, which eliminates the Dexter energy transfer between the two emitters. The color of the light emission changes from bluish white to yellowish white via pure white with



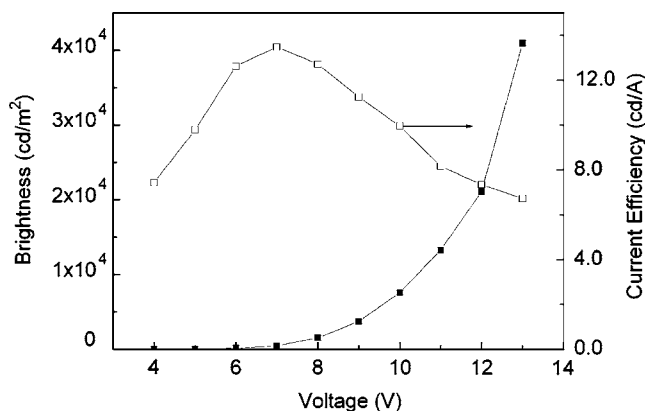


FIG. 4. Current efficiency-brightness-voltage characteristics of device I.

CIE coordinates (0.33,0.34) with  $x$  increasing from 0 to 8 nm, corresponding to current efficiency increases from 5.9 to 12.4 cd/A. The increasing current efficiency can be attributed to the increasing emission of (F-BT)<sub>2</sub>Ir(acac) which is more efficient than DPVBi. Devices B–D all emit white light, and device C produces fairly pure white light with CIE coordinates (0.33, 0.34) at 1000 cd/m<sup>2</sup>.

Performances of this kind of WOLEDs can be further improved by adjusting the concentration of phosphorescent materials or thickness of the orange phosphorescent emitting layer. More efficient WOLEDs are demonstrated by fixing the thickness of interlayer at 2 nm and adjusting the thickness of CBP:(F-BT)<sub>2</sub>Ir(acac). The structures of WOLEDs are as follows: ITO/m-MTDATA (30 nm)/NPB(20 nm)/DPVBi (15 nm)/CBP (2 nm)/CBP: 12% (F-BT)<sub>2</sub>Ir(acac) ( $y$  nm)/BCP (10 nm)/Alq<sub>3</sub> (30 nm)/LiF (0.8 nm)/Al ( $y=5, 6, 7, 9, 10,$  and  $12$  nm for devices E, F, G, H, I, and J, respectively). Figure 2 shows the normalized EL spectra of WOLEDs E–J at 7 V. The orange emission from (F-BT)<sub>2</sub>Ir(acac) increases because more excitons will be recombined in CBP:(F-BT)<sub>2</sub>Ir(acac) layer with the increasing thickness of the layer. The inset in Fig. 2 is the chromaticity and efficiency of devices E–J. Devices F–J all emit white light. The device I with 10-nm-thick CBP:(F-BT)<sub>2</sub>Ir(acac) layer emits highly efficient pure white light with CIE coordinates (0.33, 0.34), which is close to the equienergy white point (0.33, 0.33). Figure 3(a) shows the normalized EL spectra of the device I at different luminances. The spectra show only a little change when the luminance ranges from 50 to 5000 cd/m<sup>2</sup>. Figure 3(b) shows the CIE coordinates from 5 to 13 V. We can see that the CIE coordinates are fairly stable over a range of operation voltages and the region is just around the equienergy white point. Current efficiency-brightness-voltage characteristics of the device I are shown in Fig. 4. Device I has a maximum current efficiency and brightness of 13.4 cd/A and 40 960 cd/m<sup>2</sup>, respectively. Besides, the device has an acceptable color rendering index of 71.

In summary, we have demonstrated an efficient WOLED based on blue fluorescent and orange phosphorescent emissions. Performances of the device can be improved by introducing a 2 nm bipolar transport CBP layer between the two layers. A white emission with a CIE of (0.33, 0.34) and a color rendering index of 71 was obtained. The maximum luminance and current efficiency of the device are 40 960 cd/m<sup>2</sup> and 13.4 cd/A, respectively.

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