

## Improved color stability in white phosphorescent organic light-emitting diodes using charge confining structure without interlayer

Sung Hyun Kim and Jyongsik Jang

School of Chemical and Biological Engineering, Seoul National University, Shinlim-dong, Kwanak-gu, Seoul 151-742, Korea

Jun Yeob Lee<sup>a)</sup>

Department of Polymer Science and Engineering, Dankook University, Jukjeon-dong Suji-gu Yongin-si Gyeonggi-do 448-701 Korea

(Received 25 July 2007; accepted 30 August 2007; published online 20 September 2007)

Color stability of white organic light-emitting diodes was improved by using a charge confining device structure, which can confine charges at the center of the emitting layer. A red phosphorescent emitting layer was sandwiched between blue phosphorescent emitting layers and there was little change of color coordinate from 100 to 10 000 cd/m<sup>2</sup>. © 2007 American Institute of Physics.

[DOI: 10.1063/1.2786853]

White organic light-emitting diodes (WOLEDs) have gained considerable interest in the last decade for their applications as a large size display, a backlight for liquid crystal display, and a light source for general illumination. They have many advantages over other displays or light sources such as flexibility, design freedom, thin and light, distributed light emission, and low cost manufacturing.

There have been many studies about developing high performance WOLEDs to improve light-emitting efficiency, lifetime, and color stability.<sup>1–15</sup> Various materials and device architectures have been reported and phosphorescent WOLEDs with stacked structure gave good device performances compared with other devices.<sup>1–10</sup> Sun *et al.* developed a hybrid WOLED with fluorescent blue emitter and phosphorescent red and green emitters.<sup>1</sup> A high quantum efficiency of 18.7% was obtained because both singlet and triplet excitons could effectively contribute to the white light emission. Other than these, various phosphorescent WOLEDs with different stack structures were reported.<sup>2–10</sup> Hole blocking layer free phosphorescent WOLED was developed by Lei *et al.*<sup>4</sup> and phosphorescent dopant sensitized fluorescent WOLEDs were useful to get high quantum efficiency in WOLEDs.<sup>14,15</sup> Single layer WOLEDs with Pt based blue phosphorescent dopant material could also give an efficient white emission due to the excimer formation within the emitting layer.<sup>9</sup> However, the color stability of these devices could not be good because electrons and holes could not be confined inside the emitting layer. Charge leakage at high electric field induced the change of emission spectrum of WOLEDs, resulting in the shift of color coordinates at high current density.<sup>1</sup>

In this work, charge confining phosphorescent WOLEDs were developed to improve the color stability of phosphorescent WOLEDs. Two color stacked devices were fabricated and the color stability of WOLED was investigated according to stacking structure of WOLEDs. A sandwiched structure of the blue and red phosphorescent emitters was prepared and its color stability was compared with that of conventional WOLEDs.

Two different device configurations were used in this work and they were indium tin oxide (ITO) (150 nm)/N,N'-diphenyl-N,N'-bis-[4-(phenyl-*m*-tolyl-amino)-phenyl]-biphenyl-4,4'-diamine (DNTPD) (60 nm)/N,N'-di(1-naphthyl)-N,N'-diphenylbenzidine (NPB) (20 nm)/N,N'-dicarbazolyl-3,5-benzene (mCP) (10 nm)/mCP: iridium(III)bis(4,6-(di-fluorophenyl)-pyridinato-*N,C2'*) picolinate (FIrpic) (8 nm)/(4,4'-N,N'-dicarbazole)biphenyl (CBP): iridium(III) bis(1-phenylquinoline) acetylacetonate (Ir(piq)<sub>2</sub>acac) (12 nm)/mCP:FIrpic (8 nm)/2,9-dimethyl-4,7-diphenyl-1,10-phenanthroline(BCP) (5 nm)/tris (8-hydroxyquinoline) aluminium (20 nm)/LiF (1 nm)/Al (200 nm) and ITO/DNTPD (60 nm)/NPB (20 nm)/mCP (10 nm)/mCP:FIrpic (25 nm)/CBP:Ir(piq)<sub>2</sub>acac (5 nm)/BCP (5 nm)/Alq<sub>3</sub> (20 nm)/LiF (1 nm)/Al (200 nm). Device configurations used in this experiment are shown in Fig. 1. Device I has a conventional two color white device structure, while device II has a red emitting layer sandwiched between blue emitting layers. The thickness of organic layers was optimized to give white color coordinate of (0.33,0.35) for each device structure. Current density–voltage–luminance (*I-V-L*) characteristics and electroluminescence (EL) spectra of phosphorescent light emitting diodes were

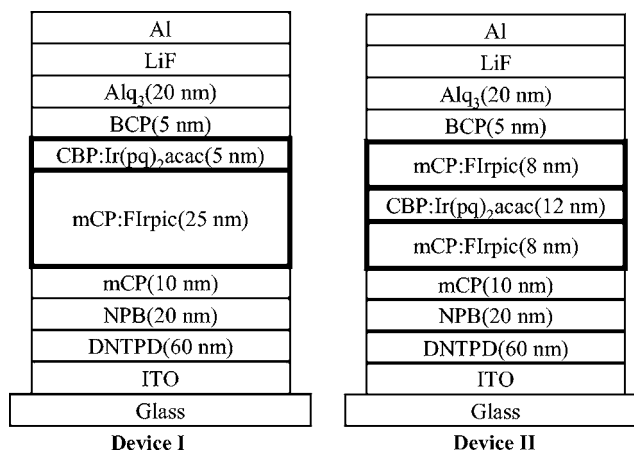
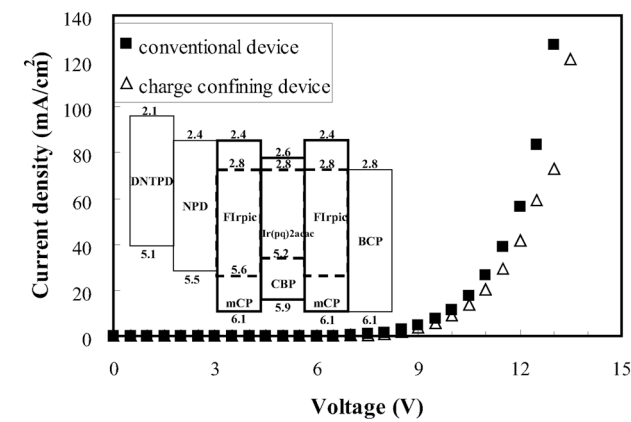
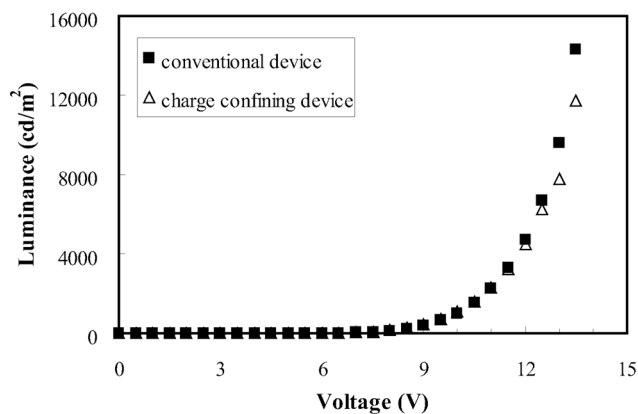


FIG. 1. Device configurations for conventional and charge confining devices.

<sup>a)</sup> Author to whom correspondence should be addressed. Tel.: 82-31-8005-3585. FAX: 82-31-8005-3585. Electronic mail: leej17@dankook.ac.kr



(a)



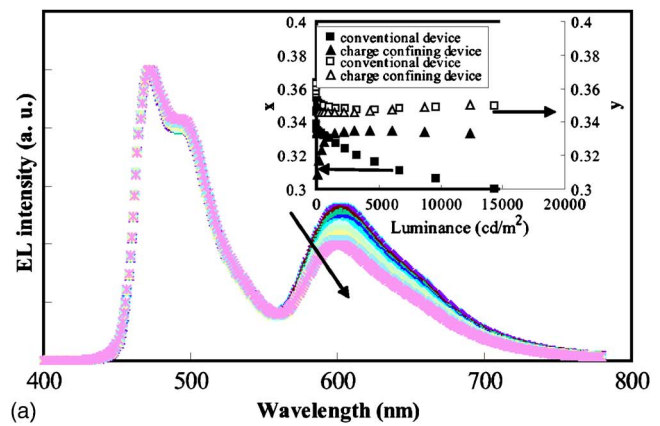
(b)

FIG. 2. Current density–voltage–luminance characteristics of conventional and charge confining devices (inset: energy level diagram): (a) Current density–voltage and (b) Luminance–voltage.

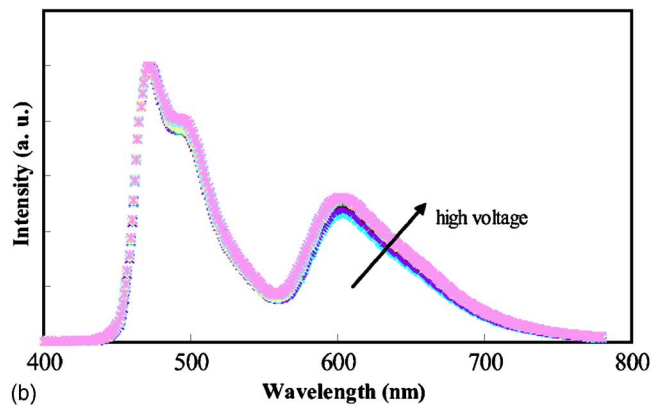
measured with Keithley 2400 source measurement unit and CS 1000 spectrophotometer.

Color stability of WOLEDs is important in that there should be no change of color over wide luminance range when they are used in displays and light sources. One approach to get a good color stability is to apply exciton confining structure, which has interlayers at the interface of emitting layers.<sup>1</sup> The interlayer controls the diffusion of excitons and charges into and out of the emitting layers. However, the device structure is complicated because interlayers should be inserted between the emitting layers to guarantee a constant color at different luminances. In this work, a charge confining device structure without interlayers was developed to improve the color stability of WOLEDs

In our previous work, it was possible to get high efficiency in green phosphorescent organic light-emitting diodes by sandwiching a narrow bandgap host material between wide bandgap host materials.<sup>16</sup> Similar device structure can be used in WOLEDs and a narrow bandgap red emitter was sandwiched between wide bandgap blue emitters to get color stability through charge confinement. To investigate the charge confinement effect in WOLEDs,  $I$ - $V$  relationship of charge confining devices were measured. Figure 2 shows  $I$ - $V$  relationship of the charge confining device compared with a conventional device. Current density, which reflects charge injection and transport inside the device, was low in the charge confining device, indicating that the charge density is



(a)



(b)

FIG. 3. (Color online) Electroluminescence spectra of conventional and charge confining devices according to the driving voltage of the devices (inset:  $x$ ,  $y$  index of color coordinate): (a) Conventional device and (b) Charge confining device

low in the charge confining device. The low current density in the charge confining device can be explained by limited electron injection and charge trapping effect of red emission layer at the center of the light emitting layer. Energy level diagram of the charge confining device is shown in Fig. 2 as an inset. Electron injection from BCP to mCP layer is rather limited due to the high energy barrier for electron injection compared with electron injection from BCP to CBP. Therefore, current density decreases in the charge confining device. Charge trapping by red emitting layer is also responsible for low current density in the charge confining device. Holes are injected from hole transport layer to red emission layer through the blue emission layer. Holes injected from blue layer to red emission layer are trapped by the CBP and red emitting Ir(piq)<sub>2</sub>acac dopant. In particular, holes trapped by red emitter cannot be transported to the blue emitting layer near the BCP due to the high energy barrier for hole injection from Ir(piq)<sub>2</sub>acac to mCP or FIrpic. Holes cannot be effectively transported from CBP to mCP due to an energy barrier of 0.2 eV for hole injection. Electrons injected from BCP to red emitting layer through blue emitting layer are also trapped by red emitting layer due to energy barrier for electron injection from Ir(piq)<sub>2</sub>acac to FIrpic or CBP to mCP. Therefore, holes and electrons are trapped inside the red emitting layer and the low current density was observed in the charge confining device. Luminance also showed the same tendency as current density, as shown in Fig. 2.

Holes and electrons trapping by red emitting layer can be beneficial to the color stability of WOLEDs because charges cannot be injected from red to blue emitting layers.

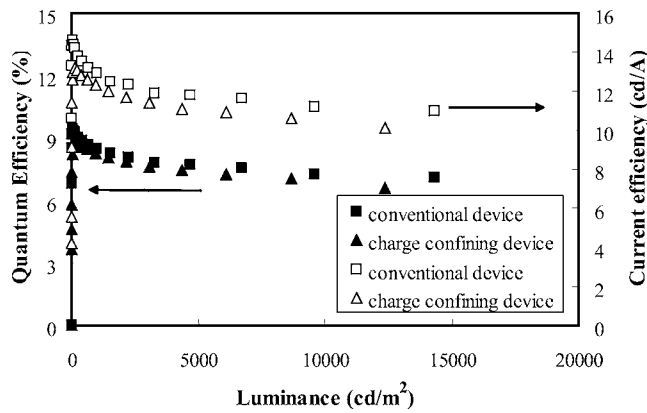


FIG. 4. Quantum efficiency and current efficiency curves of conventional and charge confining devices.

Figure 3 shows the EL spectra of conventional and charge confining WOLEDs. All EL spectra were normalized to compare the relative change of blue and red emission peaks. There was no change of EL spectra in the charge confining device according to the driving voltage of the devices, while the decrease of red emission peak was observed at high voltage in the conventional device. The decrease of red emission peak at high voltage is due to the electron injection from red to blue layer. More excitons are formed in the blue emitting layer due to high electron density at high voltage and the relative intensity of red emission is decreased. In the charge confining device, the decrease of red emission was not observed in spite of the same energy barrier for electron injection. Even though energy barrier for electron injection is the same for the two devices, low electron density in the charge confining device decreases the electron overflow from red emitting layer to blue emitting layer, resulting in no change of EL spectra at high driving voltage. Color coordinate of the charge confining device was kept (0.33,0.35) over all the luminance range investigated except at the luminance level lower than 100  $\text{cd/m}^2$ . Charge injection into red emission layer was not efficient at low voltage and the blueshift of EL spectra was observed. Color coordinate of the charge confining device at 50  $\text{cd/m}^2$  was (0.31,0.35) and it was even blueshifted at 7  $\text{cd/m}^2$  to (0.28,0.35). Compared with the charge confining device, color coordinate of conventional device was blueshifted from (0.34,0.35) to (0.30,0.35) as the luminance increased. Change of the color coordinate of conventional and charge confining devices is shown in the inset of

Fig. 3 according to luminance. Both  $x$  and  $y$  were kept constant from 100 to 10 000  $\text{cd/m}^2$  in charge confining devices, while a gradual decrease of  $x$  was observed in conventional device.

The quantum efficiency of the charge confining device at 500  $\text{cd/m}^2$  was 8.2% and a high current efficiency of 12.7  $\text{cd/A}$  was obtained. The efficiency value was fairly stable. The quantum efficiency was 7.2% and the current efficiency was 10.8 at 5 000  $\text{cd/m}^2$ . Quantum efficiency and current efficiency of the charge confining device and conventional device are shown in Fig. 4.

In conclusion, color stability of WOLEDs could be improved by using a charge confining device structure with red emitting layer sandwiched between blue emitting layers. There was a little change of emission spectrum at different luminances due to the charge confinement inside the emitting layers.

This work was supported by future technology development program of MOCIE/ITEP [2006–10028439, OLED Lighting].

- <sup>1</sup>Y. Sun, N. C. Giebink, H. Kanno, B. Ma, M. E. Thompson, and S. R. Forrest, *Nature (London)* **440**, 908 (2006).
- <sup>2</sup>H. Kanno, R. J. Holmes, Y. Sun, S. Kena-Cohen, and S. R. Forrest, *Adv. Mater. (Weinheim, Ger.)* **18**, 339 (2006).
- <sup>3</sup>H. Kanno, N. C. Giebink, Y. Sun, and S. R. Forrest, *Appl. Phys. Lett.* **89**, 023503 (2006).
- <sup>4</sup>G. Lei, L. Wang, and Y. Qiu, *Appl. Phys. Lett.* **88**, 103508 (2006).
- <sup>5</sup>G. Cheng, Y. Zhang, Y. Zhao, Y. Lin, C. Ruan, S. Liu, T. Fei, Y. Ma, and Y. Cheng, *Appl. Phys. Lett.* **89**, 043504 (2006).
- <sup>6</sup>B. W. D'Andrade and S. R. Forrest, *J. Appl. Phys.* **94**, 3101 (2003).
- <sup>7</sup>B. W. D'Andrade, R. J. Holmes, and S. R. Forrest, *Adv. Mater. (Weinheim, Ger.)* **16**, 624 (2004).
- <sup>8</sup>S. Tokito, T. Iijima, T. Tsuzuki, and F. Sato, *Appl. Phys. Lett.* **83**, 2459 (2003).
- <sup>9</sup>E. L. Williams, K. Haavisto, J. Li, and G. E. Jabbour, *Adv. Mater. (Weinheim, Ger.)* **19**, 197 (2007).
- <sup>10</sup>H. Kanno, Y. Sun, and S. R. Forrest, *Appl. Phys. Lett.* **86**, 263502 (2005).
- <sup>11</sup>S. Hsu, C. Lee, S. Hwang, and C. H. Chen, *Appl. Phys. Lett.* **86**, 253508 (2005).
- <sup>12</sup>T. Chua, J. Chen, S. Chen, and C. H. Chen, *Appl. Phys. Lett.* **89**, 113502 (2006).
- <sup>13</sup>B. C. Krummacker, V. Choong, M. K. Mathai, S. A. Choulis, F. So, F. Jermann, T. Fiedler, and M. Zachau, *Appl. Phys. Lett.* **88**, 113506 (2006).
- <sup>14</sup>Y. Zhang, G. Cheng, Y. Zhao, J. Hou, and S. Liu, *Appl. Phys. Lett.* **86**, 011112 (2005).
- <sup>15</sup>G. Lei, L. Wang, and Y. Qiu, *Appl. Phys. Lett.* **85**, 5403 (2004).
- <sup>16</sup>S. H. Kim, J. Jang, and J. Y. Lee, *Appl. Phys. Lett.* **90**, 253511 (2007).