Simplified Bilayer White Phosphorescent Organic Light-Emitting Diodes

Jonghee Lee, Woo Jin Sung, Chul Woong Joo, Hyunsu Cho, Namsung Cho, Ga-Won Lee, Do-Hoon Hwang, and Jeong-Ik Lee

We report on highly efficient blue, orange, and white phosphorescent organic light-emitting diodes consisting only two organic layers. Hole transporting 4, 4,' 4"-tris (N-carbazolyl)triphenylamine (TcTa) and electron transporting 2-(diphenylphosphoryl) spirofluorene (SPPO1) are used as an emitting host for orange light-emitting bis(3-benzothiazol-2-yl-9-ethyl-9H-carbazolato) (acetoacetonate) iridium ((btc)2(acac)Ir) and blue light-emitting iridium(III)bis(4,6-difluorophenyl-pyridinato-N,C2') picolinate (FIrpic) dopant, respectively. Combining these two orange and blue light-emitting layers, we successfully demonstrate highly efficient white PHOLEDs while maintaining Commission internationale de l'éclairage coordinates of ($x = 0.373$, $y = 0.443$). Accordingly, we achieve a maximum external quantum, current, and power efficiencies of 12.9%, 30.3 cd/A, and 30.0 lm/W without out-coupling enhancement.

Keywords: Organic light-emitting diodes, OLED, white, phosphorescent, bilayer, simple.

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I. Introduction

Organic light-emitting diodes (OLEDs) are attracting widespread attention as next-generation low-cost, high-efficiency thin-film electroluminescent devices for both flat panel displays and lighting applications. While conventional fluorescent tubes and market-pioneering white inorganic light-emitting diodes are currently holding most of the market share in the lighting industry, white OLEDs (WOLEDs) could be a very competitive candidate due to their unique advantages, including low operating voltages, high power efficiencies, and suitability for processing on flexible substrates. WOLEDs for solid-state lighting applications require high efficiency, high color rendering index, high color stability, and appropriate color temperature [1]–[5].

There are various methods for highly efficient WOLEDs. In particular, to use phosphorescent materials is one effective way to get high efficiency in WOLEDs due to their ability to efficiently utilize both singlet and triplet excitons. However, phosphorescent OLEDs (PHOLEDs) require a complicated device structure with numerous organic layers to improve charge injection, transport, balance, and exciton confinement. Since the complicated structures increase the manufacturing cost, simplified device structures are desirable for OLED applications.

In this work, we have demonstrated a simplified white PHOLED consisting of only two organic layers; that is, a hole transporting–type orange emitting layer (EML) and an electron transporting–type blue EML. We believe that this simple design concept can provide a new avenue for achieving high-performance WOLEDs for lighting applications.

II. Experiments

As shown in Fig. 1, three simplified PHOLEDs in the current study (Device A-C) were fabricated as follows:

- Device A (blue) – indium tin oxde (ITO)/TcTa (50 nm)/ SPPO1: FIrpic (50 nm, 10%)/LiF/Al
- Device B (orange) – ITO/TcTa: $(btc)_2(acac)Ir$ (50 nm, 7%)/ SPPO1 (50 nm)/LiF/Al
- Device C (white) – ITO/TcTa: $(btc)_2(acac)Ir$ (50 nm, 7%)/ SPPO1: FIrpic (50 nm, 10%)/LiF/Al

The hole-transporting material, TcTa, with a high triplet level (2.85 eV), and the high-lying lowest unoccupied molecular orbital (LUMO) energy level of 2.4 eV, which can efficiently confine the triplet energy of the orange phosphorescent emitter ($(btc)_2(acac)Ir$) and electrons, is selected as the hole-transport/host of orange EML [6], [7]. The electron-transporting material SPPO1 with a high triplet level (2.90 eV) and the low-lying highest occupied molecular orbital (HOMO) energy level of 6.5 eV, which can efficiently confine the triplet energy of the blue phosphorescent emitter (FIrpic) and holes, is selected as the hole-transport/host of blue EML. The chemical structures of the materials and energy level diagrams used in this study are shown in Figs. 2 and 3 (the energy levels are taken from the literature) [8]–[10], respectively.

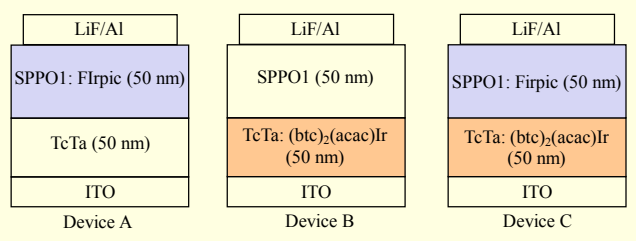

Fig. 1. Device structures of blue (device A), orange (device B), and white (device C) PHOLEDs tested in this study.

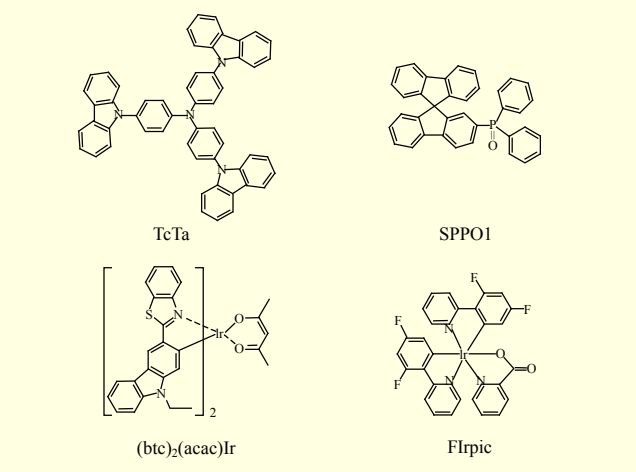

Fig. 2. Chemical structures for materials tested in this study.

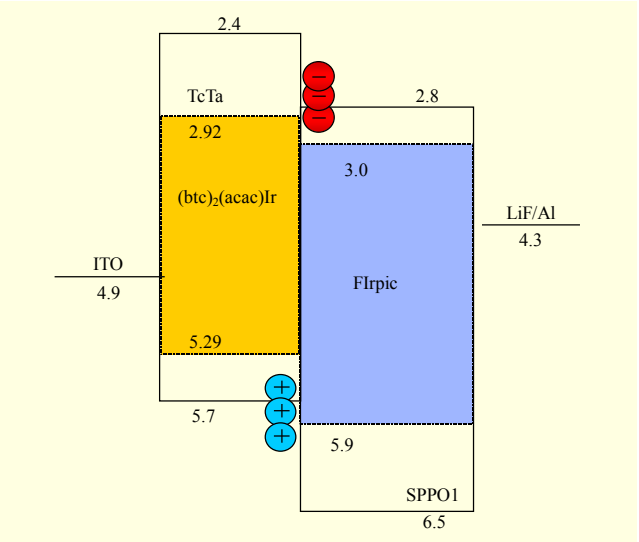

Fig. 3. Energy level diagrams for materials tested in this study.

ITO was cleaned using a standard oxygen plasma treatment. The OLED grade materials were purchased and used without further purification. All organic layers were deposited in a high vacuum chamber below 5×10^{-7} Torr, and thin LiF and Al films were deposited as a cathode electrode. The OLEDs were transferred directly from a vacuum into an inert environment glove-box, where they were encapsulated using a UV-curable epoxy and a glass cap with a moisture getter. The electroluminescence spectrum was measured using a Minolta CS-1000. The current–voltage (J–V) and luminescence-voltage (L-V) characteristics were measured using a current/voltage source/measure unit (Keithley 238) and a Minolta CS-100, respectively.

III. Results and Discussion

To develop efficient PHOLEDs, the effective confinement of both the charge carriers and the triplet excitons is necessary. By stacking two organic layers with different charge-transporting properties, the charge carriers (holes and electrons) are accumulated at the interface of TcTa and SPPO1. Furthermore, the high-lying LUMO level of TcTa and the low-lying HOMO of SPPO1 level help to confine the charge carriers. Therefore, the effective hole/electron recombination could be achieved, as is shown in Fig. 3.

Figure 4 shows the current density-voltage-luminance (J-V-L) curves of the PHOLEDs (devices A–C). To obtain more efficient WOLEDs, particularly to achieve high luminance efficacy for solid-state lighting application, it is very desirable that the driving voltage of the WOLEDs be lowered. The turn-on voltages of devices A, B, and C are approximately 3.0 V. In particular, the relatively low turn-on voltage (3.2 V at 1 cd/m^2)

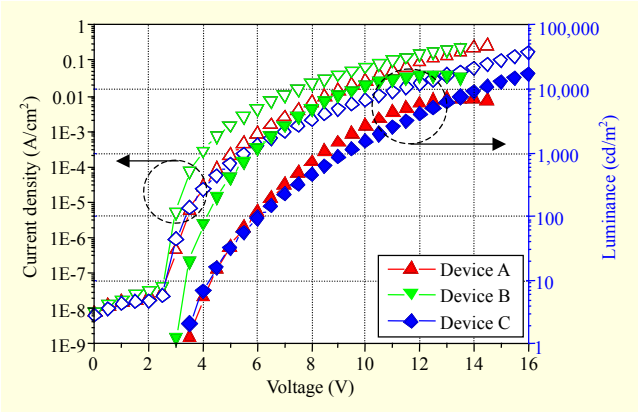

Fig. 4. Current density-voltage-luminescence-voltage (J-V-L) characteristics of devices A–C.

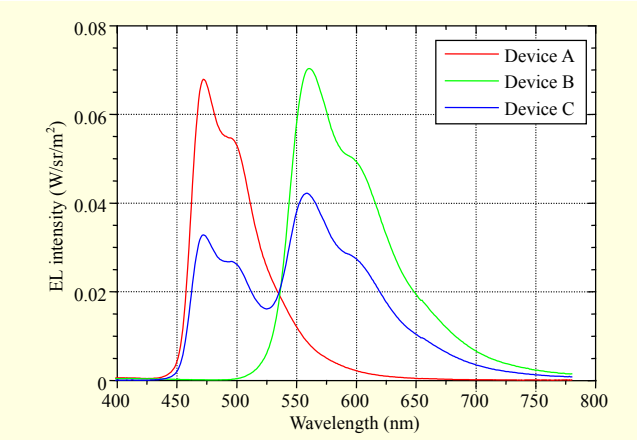

Fig. 5. EL spectra of devices A–C at driving current of 10 mA/cm^2.

of the white PHOLED (device C) with only two layers is noticeable because it is almost similar in value to that of the complicated conventional white PHOLEDs. This could be explained by the following: (a) the acceptable low-lying HOMO energy level (5.7 eV) and the high hole mobility of TcTa for hole carrier and (b) the adequate high-lying LUMO energy level (2.8 eV) and the high electron mobility of SPPO1 for the hole carrier [8], [11]. The driving voltages at 100 cd/m^2 of devices A, B, and C are 5.8 V, 4.1 V, and 6.0 V, respectively. The maximum luminance values of 7,108 cd/m^2, 16,410 cd/m^2, and 18,330 cd/m^2 were achieved for devices A–C.

The electroluminescence (EL) spectra at a driving current density of 10 mA/cm^2 for devices A–C are shown in Fig. 5. The EL spectra of devices A and B exhibited peak wavelengths at 472 nm and 559 nm, respectively. These emissions correspond to the peak wavelengths of the EL spectra of the single-color OLEDs using the FIrpic and $(btc)_2(acac)Ir$, respectively. For device C, we could easily find the white EL emission consisting of blue (FIrpic) and orange ($(btc)_2(acac)Ir$) emissions, by which we mean that the simplified white

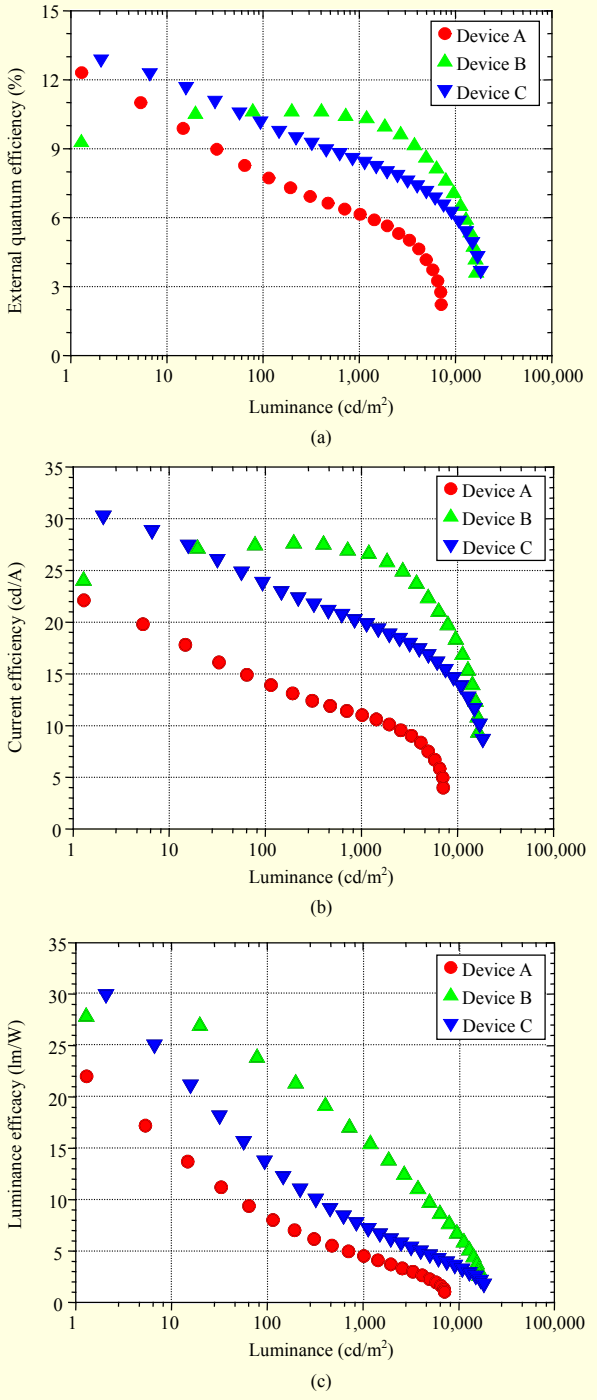

Fig. 6. External quantum, current, luminance efficiency vs. luminance characteristics of devices A–C.

PHOLED was successfully demonstrated with only two organic layers. The CIE coordinates and correlated color temperature (CCT) of WOLEDs (device C) at a driving current density of 10 mA/cm^2 are (0.373, 0.48) and 4,512 K, respectively.

The external quantum, current, and luminance efficiencies of

the emitted light in the forward direction of the WOLEDs versus luminance are plotted in Fig. 6. The quite high peak external quantum efficiency of 12.3% (device A), and 10.6% (device B) are indicating a successful effective confinement of both the charge carriers and the triplet excitons by stacking two organic layers with different charge-transporting properties. Finally, maximum external quantum, current, and power efficiencies of simplified white PHOLEDs (device C) were achieved without any out-coupling enhancement — 12.9%, 30.3 cd/A, and 30.0 lm/W, respectively. The reduced efficiency at a high luminance region (that is, *roll-off* phenomenon) for blue (A) and white (C) OLED comes from a poor electrical optimization (triplet-triplet annihilation (TTA) or triplet-polaron annihilation (TPA)) and low charge carrier balance in the FIrpic-based blue EML [11]–[13]. The external quantum, current, and power efficiencies of simplified white PHOLEDs (device C) at a luminance of 1,000 cd/m^2 was reduced to 8.6%, 20.3 cd/A, and 7.8 lm/W, respectively. This could be resolved by further device engineering such as an optimization of doping ratio or a use of a host mixing structure; especially, for the blue layer.

IV. Conclusion

We have demonstrated bilayer phosphorescent white OLEDs with a configuration of ITO/TcTa: orange dopant/SPPO1: blue dopant/LiF/Al. These simplified structures are also applicable to orange and blue monochromic OLEDs with common phosphorescent dopants. Efficient performance of the simplified bilayer devices is attributed to direct hole/electron injection and transport on the triplet dopants. This concept indicates a possible new direction to fabricate simplified OLEDs with competitive performance.

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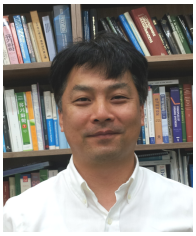

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