

# Highly color-stable and efficient hybrid white organic light-emitting devices by compensating a recombination zone shift in a single host layer



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## ABSTRACT

We have developed highly color-stable and efficient hybrid white organic light-emitting devices (WOLEDs) with multi-emission layers structure consisted of a single host layer doped with fluorescent and phosphorescent guest molecules. The blue fluorescent, red and green phosphorescent molecules were doped into the separated layers of a single host. The color stability of the WOLEDs is substantially improved by embedding an additional blue fluorescent layer which compensates the color change due to the recombination zone shift. The Commission Internationale de L'Eclairage coordinates of the hybrid WOLED change from (0.45, 0.46) to (0.44, 0.45) as the luminance varies from 128 to 23,460 cd/m<sup>2</sup>. The color-stable WOLED also exhibits a high maximum external quantum efficiency of 15.2% and a current efficiency of 38.8 cd/A.

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## 1. Introduction

White organic light-emitting devices (WOLEDs) have attracted much attention in the past decade because of their potential use in large area, high-resolution display and solid-state lighting applications [1,2]. Many authors have reported various device structures such as tandem [3], down conversion [4], single emission layer [5], and multiple emission layers [6–8] for WOLEDs. Especially, the devices with separate emission layers using single [6,7] or multiple host [8] materials have been extensively researched because they can provide high efficiency and easy control of white balance. The efficiency of WOLEDs has been improved by using phosphorescent emitters which can harvest singlet and triplet excitons [9]. Hybrid WOLEDs with fluorescent blue and phosphorescent red and green emitters have also been proposed for overcoming low operational stability of blue phosphors [10]. In addition to efficiency and lifetime, the color coordinate and color temperature of the device should be stable over wide luminance range for the wide applications of WOLEDs in displays and lightings. Although several groups have reported color-stable white devices [11,12], the luminance-dependent color shifts exceeding a tolerable margin are generally observed in the devices with multi-emission layers structure [13–15].

In this paper, we report highly efficient and color-stable hybrid WOLEDs with multi-emission layers using a *N,N'*-dicarbazolyl-3,5-benzene (mCP) host material. We used fluorescent blue and phosphorescent red and green guest molecules for investigating the color-stability of the hybrid WOLEDs with separately doped layers of a single mCP host layer. The fluorescent 4,4'-bis[2-(3-N-ethylcarbazoryl)vinyl]biphenyl (BCzVBi) molecule was used as a blue emitter [16]. The phosphorescent tris(2-phenyl-1-quinoline)iridium(III) [Ir(phq)<sub>3</sub>] [17] and tris(2-phenylpyridine)iridium (III) [Ir(ppy)<sub>3</sub>] [18] molecules were used as red and green emission materials, respectively. We have investigated the changes in electroluminescence (EL) spectrum and color coordinates for the various multi-emission layers structures with a single mCP host. We have also investigated the exciton formation region, energy transfer, and carrier trapping in the devices. We demonstrate the highly color-stable hybrid WOLEDs with a maximum quantum efficiency of 15.2% by embedding an additional blue fluorescent layer compensating the spectral change attributed to the recombination zone shift.

## 2. Experimental

Indium tin oxide (ITO) coated glass substrates were used for preparing the hybrid WOLEDs with fluorescent blue and phosphorescent red and green guest molecules doped into the mCP host. The sheet resistance of the ITO film was about 10 Ω/□. After defining ITO anode patterns using standard photolithography process, the

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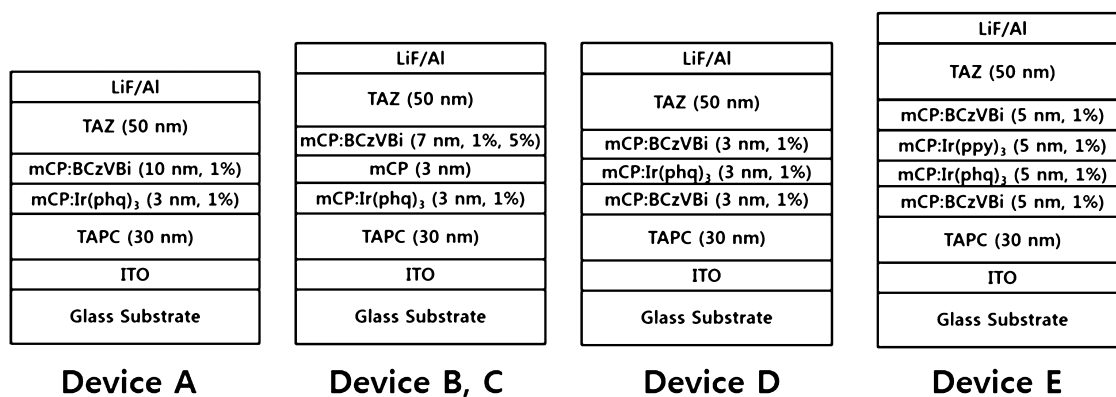


Fig. 1. Device structures of the hybrid WOLEDs with single mCP host layer.

substrates were cleaned with isopropyl alcohol and deionized water. The cleaned substrates were exposed to the oxygen plasma at 10 W before loading into the vacuum chamber. All organic and metal layers were deposited by using a vacuum thermal evaporation method in a base pressure of about  $1 \times 10^{-6}$  Torr. After depositing a 10 nm thick 1,1-bis[(di-4-tolylamino)phenyl]cyclohexane (TAPC) hole transport layer (HTL) on the patterned ITO substrate, various structures of emission layers were prepared. Fig. 1 shows the device structures of our hybrid WOLEDs. The structures of emission layers are mCP:Ir(phq)<sub>3</sub> (3 nm, 1%)/mCP:BCzVBi (10 nm, 1%), mCP:Ir(phq)<sub>3</sub> (3 nm, 1%)/mCP (3 nm)/mCP (7 nm, 1%), mCP:Ir(phq)<sub>3</sub> (3 nm, 1%)/mCP (3 nm)/mCP:BCzVBi (7 nm, 5%), mCP:BCzVBi (3 nm, 1%)/mCP:Ir(phq)<sub>3</sub> (3 nm, 1%)/mCP:BCzVBi (3 nm, 1%), and mCP:BCzVBi (5 nm, 1%)/mCP:Ir(ppy)<sub>3</sub> (5 nm, 1%)/mCP:BCzVBi (5 nm, 1%) for the devices A, B, C, D, and E, respectively. The mCP was used as a single host layer. The BCzVBi, Ir(ppy)<sub>3</sub>, and Ir(phq)<sub>3</sub> molecules were used as blue, green, and red guest molecules, respectively. A 50 nm thick 3-(biphenyl-4-yl)-4-phenyl-5-(4-tert-butyl-phenyl)-1,2,4-triazole (TAZ) electron transport layer (ETL) was deposited. After depositing organic layers, a 0.5 nm thick LiF and a 100 nm thick Al layers were sequentially evaporated through a shadow mask. The active area of the devices was 4 mm × 4 mm. Current density–voltage–luminance (J–V–L) characteristics of the devices were measured using computer controlled Keithley 2400 source-measure units and a calibrated fast Si photodiode (FDS010). EL spectrum was measured with a spectroradiometer (Minolta CS1000).

### 3. Result and discussion

Fig. 2(a) shows the EL spectra measured at various driving voltages for the device A with a structure of ITO/TAPC (10 nm)/mCP:Ir(phq)<sub>3</sub> (3 nm, 1%)/mCP:BCzVBi (10 nm, 1%)/TAZ (50 nm)/LiF/Al. The strong EL peaks at 440 and 580 nm are attributed to the emissions from BCzVBi [16] and Ir(phq)<sub>3</sub> [17] molecules, respectively. As is well known, Ir(phq)<sub>3</sub> molecule is a phosphorescent emitter where the single and triplet excitons can contribute to the emission, whereas the emission from BCzVBi molecules is due to the radiative transitions of singlet excitons. The EL spectrum varies significantly as the driving voltage increases from 4 to 8 V. The blue emission from BCzVBi molecules is much stronger than the red emission from Ir(phq)<sub>3</sub> molecules at a voltage of 4 V. The peak intensity of the emission from BCzVBi molecules is about 2.7 times higher than that of the emission from Ir(phq)<sub>3</sub> molecules at a voltage of 4 V. It can be expected that more excitons are generated in the BCzVBi doped region adjacent to the TAZ layer because of the strong hole blocking property of TAZ ETL [19]. As

the driving voltage increases from 4 to 8 V, the peak intensity of emission from Ir(phq)<sub>3</sub> molecules increases from 0.38 to 1.64 compared with that from BCzVBi molecules. These substantial spectral changes in EL emission cause the significant color instability in the device A. The Commission Internationale de L'Eclairage (CIE) coordinates vary from (0.25, 0.20) to (0.39, 0.32) as the luminance

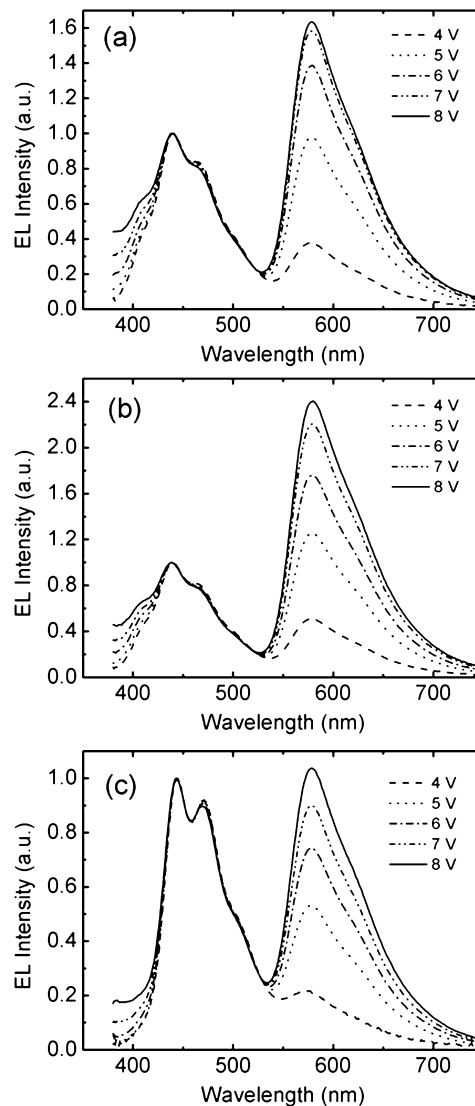


Fig. 2. EL spectra measured at various voltages for the devices (a) A, (b) B, and (c) C.

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