

# White Organic Light-Emitting Diodes Utilized by Near UV-Deep Blue Emitter and Exciplex Emission

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Numerous investigations have been made into the development of wide color gamut displays for deep-blue OLEDs, including the RGB sub pixels, and white OLEDs (WOLEDs). One of the well known deep-blue emissive dopants, *tris*(phenyl-methyl-benzimidazolyl)iridium(III) [Ir(pmb)<sub>3</sub>], successfully introduced its fascinating color coordinate of Commission Internationale de l'Eclairage (CIE) 1931 (0.17, 0.06), however there have been no reports utilizing its accomplishments as WOLEDs. In this report, using only one phosphorescent dopant, the near UV-deep blue emissive Ir(pmb)<sub>3</sub>, the WOLEDs having the CIE 1931 coordinate of (0.33, 0.38) at 100 cd/m<sup>2</sup> with a color rendering index of 85 are demonstrated. The white emission of the fabricated OLEDs are oriented from the near UV-deep blue emission of Ir(pmb)<sub>3</sub> and the successfully controlled exciplex emission, between the Ir(pmb)<sub>3</sub>-host, and the Ir(pmb)<sub>3</sub>-interfaced material.

**Keywords:** Phosphorescent OLEDs, WOLEDs, Ir(pmb)<sub>3</sub>, Exciplex.

## 1. INTRODUCTION

Since Tang et al. first reported light emissive organic electronic devices, the organic light-emitting diodes (OLEDs),<sup>1</sup> they have been widely investigated for their potential to become the next generation of displays or light sources.<sup>2</sup> Recently, the development of the deep-blue OLEDs has advanced in order to realize a wide color gamut display, including the RGB sub pixels of active-matrix OLEDs, and white OLEDs (WOLEDs).<sup>3</sup> One of the deep-blue emissive dopant, *tris*(phenyl-methyl-benzimidazolyl)iridium(III) [Ir(pmb)<sub>3</sub>], has fascinating deep blue Commission Internationale de l'Eclairage (CIE) 1931 coordinates of (0.17, 0.06),<sup>4</sup> but has not yet reported accomplishments due to some problems, including having a low photonic response near the UV-deep-blue emission to the human eye, and having too low lowest un-occupied molecular orbital energy level to be used in a conventional device structure.

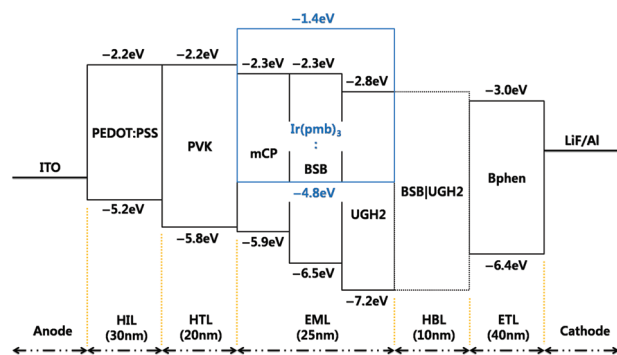
This report demonstrates the WOLEDs utilized by the single emissive layer (EML), which is doped by the near UV-deep blue emissive phosphorescent dopant Ir(pmb)<sub>3</sub>. The fabricated WOLEDs show the CIE 1931 color coordinate of (0.33, 0.38) at 100 cd/m<sup>2</sup> with a

color rendering index (CRI) of 85. The white emission of the fabricated OLEDs is oriented from the near UV-deep blue emission of Ir(pmb)<sub>3</sub> and the successfully controlled exciplex emission of Ir(pmb)<sub>3</sub>-host, and the Ir(pmb)<sub>3</sub>-interfaced material.

## 2. EXPERIMENTAL DETAILS

In this work, three WOLEDs with various emissive layers (EML) and hole blocking layers (HBL) are examined and the device structure and energy band diagram are shown in Figure 1. The indium tin oxide (ITO) is used as a transparent anode; poly(ethylenedioxythiophene):poly(styrenesulfonate) (PEDO-T:PSS), as a hole injection layer; poly(N-vinyl-carbazole) (PVK), as a hole transport layer (HTL) and also as an exciton blocking layer<sup>5-6</sup> for the HTL/EML interface; Ir(pmb)<sub>3</sub> is used as the emissive deep blue phosphorescent dopant for EML; 1,3-bis(carbazol-9-yl)benzene (mCP), 4,4'-di(triphenylsilyl)-biphenyl (BSB), and 1,4-bis(triphenylsilyl)benzene (UGH2) as the EML host; BSB or UGH2 as the HBL, depending on the EML host; 4,7-diphenyl-1,10-phenanthroline (Bphen) as the electron transport layer (ETL); lithium-fluoride (LiF) as an electron injection layer; and aluminum as a cathode. The differences between the 3 devices in this work are the

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**Fig. 1.** The device structure and energy band diagram of the fabricated WOLEDs.

**Table I.** The device configurations.

Device Configuration	EML	HBL
Device 1	mCP:Ir(pmb) <sub>3</sub>	BSB
Device 2	BSB:Ir(pmb) <sub>3</sub>	UGH2
Device 3	BSB:Ir(pmb) <sub>3</sub> /UGH2:Ir(pmb) <sub>3</sub>	UGH2

EML and the HBL and the detailed device structures are presented in Table I.

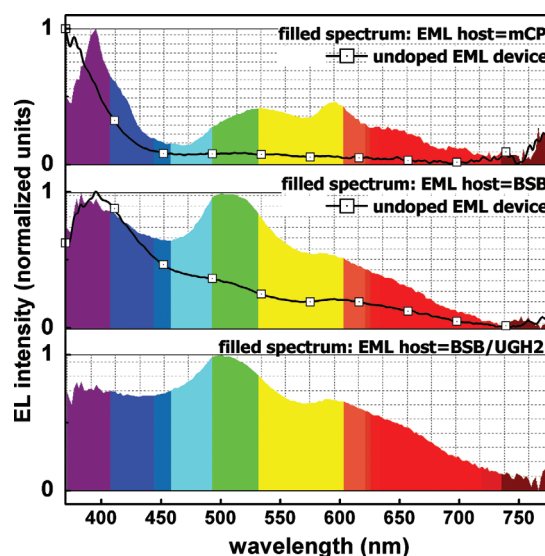
Devices are fabricated on the ITO coated glass, purchased from Samsung Corning Precision Glass. The BAYTRON-P AI4083 is used to form the PEDOT:PSS layer. The other organic materials have been commercially purchased, except for the Ir(pmb)<sub>3</sub>, which has been synthesized in the laboratory following the references.<sup>7-8</sup> Before using the ITO coated glass, it is finely cleaned, by ultrasonication, using organic solvents and deionized water. The active area of the device is 4×4 mm<sup>2</sup>. The PEDOT:PSS layer is spin-coated onto the ITO-coated glass under air atmosphere and the PVK is spin-coated using the solution in monochlorobenzene. The other organic layers, and the cathode, are subsequently deposited by a thermal evaporator, at a base pressure of about 10<sup>-6</sup> torr. The deposition rate of all the organic materials and the metals are ~1 Å/s and ~6 Å/s, respectively.

The electroluminescence (EL) is measured using the PR-670 SpectraScan Spectroradiometer (Photo Research, Inc.) and the Model 237 High-Voltage Source-Measure Unit (Keithley Instruments, Inc.). The devices are measured in a dark box and in an air atmosphere.

### 3. RESULTS AND DISCUSSION

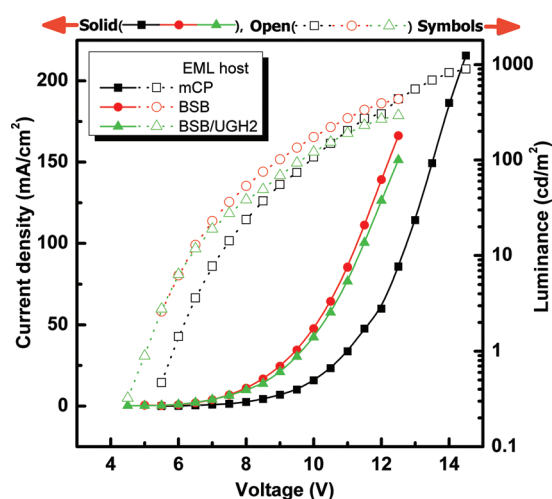
Since the Ir(pmb)<sub>3</sub> is known as a deep-blue phosphorescent dopant, in this work, the OLEDs utilized by Ir(pmb)<sub>3</sub> doped EML show the white emission, giving rise to WOLEDs.

Figure 2 shows the electroluminescence (EL) spectra of the fabricated WOLEDs. Interestingly, when the doping concentration of the Ir(pmb)<sub>3</sub> increases, the EL spectra of the Ir(pmb)<sub>3</sub> doped single EML devices show the



**Fig. 2.** The electroluminescence (EL) spectra of fabricated WOLEDs. The filled spectra represents the EL spectra of fabricated WOLEDs, and the square symbol represents the EL spectra of un-doped emissive layer only device.

green and red emission, which comes from exciplex formations of Ir(pmb)<sub>3</sub> between the EML host and HBL. This is clearly seen, when comparing the EL spectra of devices 1 and 2 with their undoped devices. In the case of the device 1 structure without Ir(pmb)<sub>3</sub> doping (undoped device), the excitons are generated on the EML/HBL interface, and emit mainly near the UV of the mCP/BSB bilayer emitter, while the Ir(pmb)<sub>3</sub> doped device shows the main peak of Ir(pmb)<sub>3</sub> at 410 nm. Furthermore, when the lower Ir(pmb)<sub>3</sub> doping concentration is applied, the green-red exciplex emission becomes weaker, and the EL spectrum changes into something like an undoped device. From the above results, the realization of the green-red exciplex emission has been clearly explained. On the other hand, in the case of the device 2 structures, the green-red exciplex emission, of both doped and undoped devices, becomes much stronger than that of device 1. This emission spectrum change seems to originate from the changed EML and HBL. The EML host is substituted from the mCP in the device 1 structure, to the BSB in the device 2 structure. From the stronger green-red exciplex emission of device 2, the origin of the exciplex formation is assumed to be the Ir(pmb)<sub>3</sub> and BSB. However, the undoped device still shows the green-red emission, which could be explained as originating from the higher HOMO energy level of the BSB EML host, and the UGH2 HBL of device 2, than that of the device 1. The increased hole injection barrier at the HTL/EML interface induces increased exciton generation at the HTL/EML (PVK/BSB) interface, and results in the green emission from the PVK at the PVK/BSB interface, due to a lower triplet energy ( $E_T$ ) of PVK ( $E_T = 3.0$  eV,<sup>5</sup>) than BSB ( $E_T = 3.5$  eV,<sup>9</sup>). Also, the increased red emission

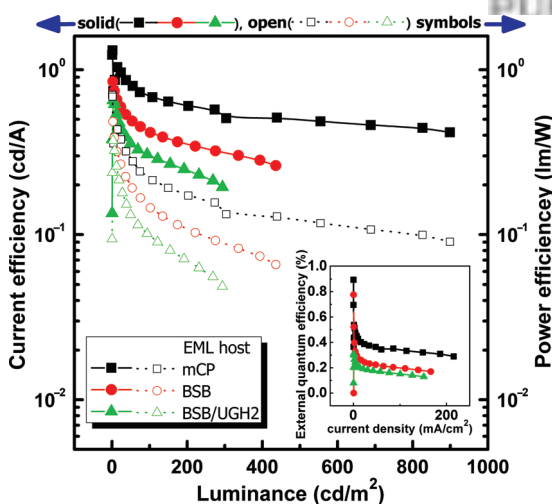


**Fig. 3.** The current density and luminance curve as a function of the applied voltage.

in the undoped device comes from the HBL/ETL interface. The lower hole injection at the EML/HBL interface in device 2 ( $\Delta\text{HOMO}_{\text{UGH2-BSB}} = 0.7 \text{ eV}$ ) than device 1 ( $\Delta\text{HOMO}_{\text{BSB-mCP}} = 1.6 \text{ eV}$ ), increases the possible exciton generation at the HBL/ETL interface, then the Bphen ETL based exciplex emission is realized.

Figures 3 and 4 show the EL characteristics of the fabricated WOLEDs, and Table II shows the summarized device performances.

Figure 3 shows the current density and luminance as a function of the applied voltage. Device 1 shows the highest peak luminance but device 1 has a comparably higher driving voltage than devices 2 and 3. This higher driving voltage comes from the highest injection barrier between the highest occupied molecular orbital (HOMO) energy level of the interfaced materials at the EML/HBL



**Fig. 4.** The current and power efficiency curves as a function of luminance. The inset shows the external quantum efficiency as a function of the current density.

**Table II.** Summary: performances of the fabricated WOLEDs.

Device	Peak EL property		At 100 cd/m <sup>2</sup>		
	EQE (%)	PE (lm/W)	EQE (%)	CIE 1931 (x, y)	CRI
Device 1	0.89	0.70	0.41	0.33, 0.38	85
Device 2	0.76	0.48	0.24	0.26, 0.35	72
Device 3	0.31	0.37	0.18	0.27, 0.33	79

interface ( $\Delta\text{HOMO}_{\text{BSB-mCP}} = 1.6 \text{ eV}$ ). Devices 2 and 3 have similar structures, and show similar current injection characteristics.

Figure 4 shows the current and power efficiencies as a function of luminance. Among devices 1–3, device 1 shows the overall highest EL efficiencies; at a luminance of 100 cd/m<sup>2</sup>, device 1 shows the highest external quantum efficiency (EQE) of 0.41% with a high CRI of 85, while those of devices 2 and 3 are (0.24%, 72) and (0.18%, 79), respectively. Since the BSB ( $E_T = 3.5 \text{ eV}$ )<sup>9</sup> and UGH2 ( $E_T = 3.5 \text{ eV}$ )<sup>9</sup> has a high triplet energy, sufficient to be the deep-blue EML host material, it is difficult to establish efficient OLEDs with them than mCP EML host, due to their high HOMO energy levels. Since the EL efficiency is low (EQE = 0.41%, at 100 cd/m<sup>2</sup>), the CRI is high enough to be used as a white light source and it is believed that, the device efficiency could be enhanced by modulating the structural engineering including the application of a highly efficient carrier injection material, p-i-n doping technology, etc.

#### 4. CONCLUSION

The WOLEDs utilized by the Ir(pmb)<sub>3</sub> doped EML have been demonstrated. The well known deep-blue emissive phosphorescent dopant Ir(pmb)<sub>3</sub> has been used to utilize, not only the blue emission but also the white emission, by exciplex formation between the EML host and the HBL. Modulating the exciplex formation by controlling the doping concentration of the emissive dopant, and by applying various EML hosts and HBL materials, the realization of the white emission with only one phosphorescent emissive dopant is possible. The WOLED with the Ir(pmb)<sub>3</sub> doped single EML having the high CRI of 85 and CIE 1931 of (0.33, 0.38) has been demonstrated.

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