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# Efficient charge balance in blue phosphorescent organic light emitting diodes by two types of mixed layer

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ABSTRACT

The authors have demonstrated a highly efficient and long-lifetime blue phosphorescent organic light emitting diode (PHOLED) that uses two types of mixed layers. The mixed layers play the role of carrier injection control and exciton generation zone extension. One of the layers is applied for mixing the hole transport layer (HTL) and host material at the HTL side for carrier injection control. The other works as a mixed electron transporting layer (ETL) and host material at the ETL side. The optimized blue PHOLED has been shown to achieve high performance owing to the mixed layer effects. It gave a maximum luminous efficiency of 25.55 cd/A, maximum external quantum efficiency of 13.05%, and lifetime of 7.24 h under 500 cd/m$^2$. These results indicate that applying mixed layers is a simple and efficient method that does not require significant structural change.


## 1. Introduction

Phosphorescent organic light emitting diodes (PHOLEDs) are of great interest for their notable impact on applications such as flat-panel displays (FPDs) and solid-state lighting [1–3]. In particular, current full-color FPDs are required to achieve both high efficiency and durability. However, it is well known that blue PHOLEDs have lower energy efficiency as well as lifetime, which hinders the commercialization of full-color FPDs [4]. A demonstration of efficiency improvement via recombination zone (RZ) shift would be a key step toward solving such problems. Although many studies have reported high performance via varied change of the emitting layer (EML) structure of PHOLEDs, which has an exciton-generating region, the combination of several distinct factors through intricate mechanisms in EML remains unclear [5,6]. In this paper, based on thorough and careful analysis of experimental results, we propose the solution that carrier injection is controlled outside the EML by a mixed layer system (MLS). The MLS has been researched actively in the context of PHOLEDs owing to its particular characteristics such as providing low driving voltage and RZ extension [7–10]. These characteristics directly influence PHOLED efficiency. Especially, an improvement in external quantum efficiency (EQE) is very important for solving the abovementioned problems of blue PHOLEDs. The EQE of a device can be defined as follows:

$$EQE(\eta_{ext}) = \gamma \times \eta_r \times \Phi_p \times \eta_p$$

where $\gamma$ is the charge balance factor and $\eta_r$ is the singlet/triplet exciton generation ratio. The effective quantum yield, $\Phi_p$, has a maximum value of unity; $\gamma$, indicates the charge balance factor, and light out coupling efficiency ($\eta_p$) is considered to be ~20%. We focused on the charge balance factor ($\gamma$) because it determines the carrier transport time, RZ width, and hole-electron recombination location. The charge balance factor ($\gamma$) is defined as follows:

$$\gamma = \gamma_{it} + \gamma_r$$

where $\gamma_{it}$ is the efficiency of injection-transport of hole and electron, and $\gamma_r$ denotes recombination probability [11,12]. Our concept involves achieving efficient charge balance, while satisfying two types of factors simultaneously by using a simple, easy method and no additional material. The factors are affinitive with RZ shift and extension, and thus the concepts of the experimental sections are divided into three types.

As noted above, we have considered effects of RZ phase and demonstrated the role of the mixed hole transport layer (HTL) and exciton confinement layer (ECL) in terms of RZ shift. That layer has different thicknesses in the HTL region of blue PHOLEDs and the partial mixed EML layer, in which the host layer and the ETL are mixed for RZ extension.

## 2. Experimental details

### 2.1. Experimental conditions & method of analysis

Indium-tin-oxide (ITO)–coated glass was cleaned in an ultrasonic bath according to the following sequence: acetone, methyl alcohol,

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0040-6090/

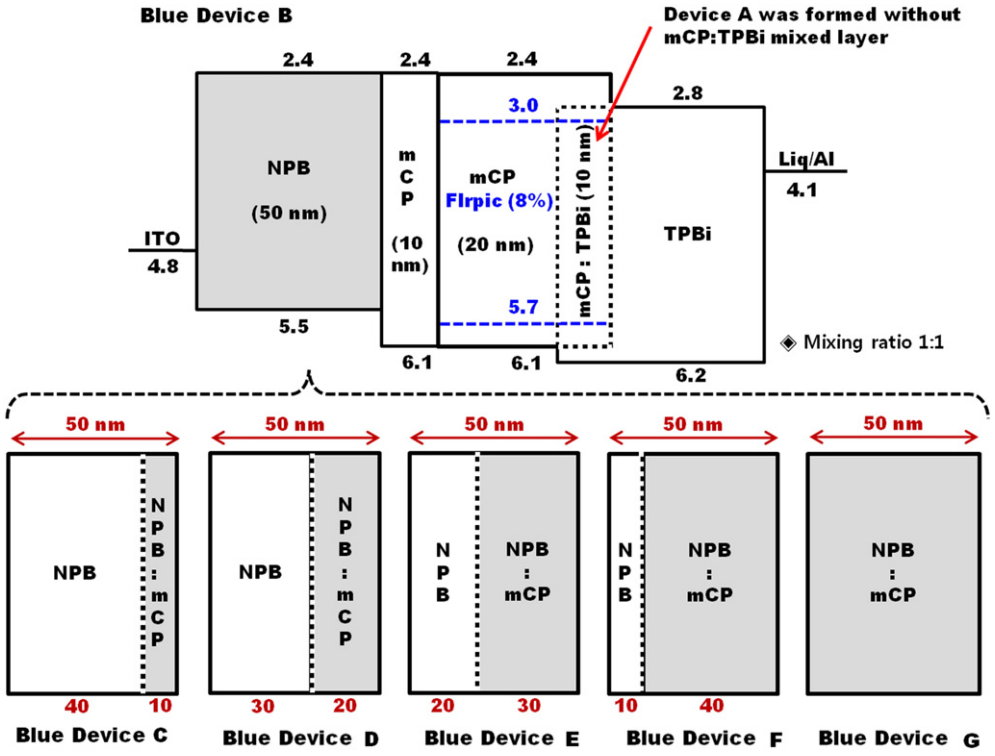


**Fig. 1.** Device structure and energy level diagrams of blue PHOLEDs (devices A, B, C, D, E, F, and G).

deionized water, and ethyl alcohol, respectively. Thereafter, it was baked in a convection oven after drying using a nitrogen gas blower. Next, pre-cleaned ITO was treated with oxygen plasma at 125 W for 2 min under low vacuum (pressure < 3 Pa). Blue PHOLEDs were fabricated by the vacuum thermal evaporation method, and all organic layers were deposited sequentially onto an ITO-coated glass substrate (10 Ω/sq, emitting area 3 × 3 $mm^2$) without a vacuum break under high vacuum (pressure < $10^{-4}$ Pa). The deposition rate of all organic materials was 0.1 nm/sec, while that of lithium quinolate (Liq) was 0.01 nm/s. Then, an aluminum (Al) electrode was deposited at 1 nm/s. With direct current voltage bias, the optical and electrical properties of green devices, including current density, luminance (L), luminous efficiency (LE), EQE, Commission International de L'Éclairage coordinates, and electroluminescence (EL) spectra characteristics, were measured using a Keithley 236 and a Chroma Meter CS-1000A, respectively. All measurements were performed under ambient conditions at room temperature.

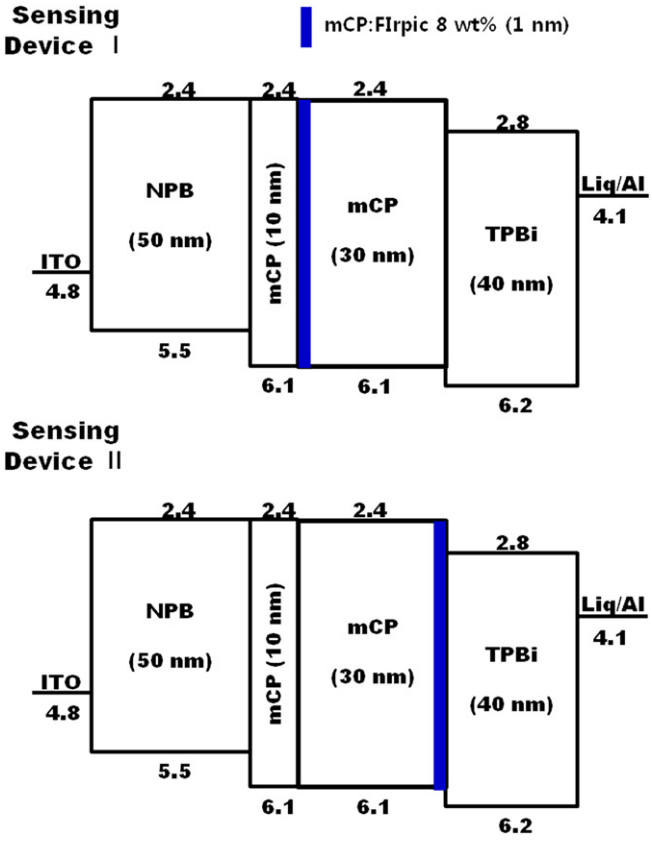


**Fig. 2.** Device structure and energy level diagrams of two types of sensing devices.

### 2.2. OLED fabrication

All mixed layers a have 1:1 mixing ratio for charge balance and RZ extension. The detailed structures of blue PHOLEDs are given as follows: ITO (180 nm); 4,4′-bis [N-(naphthyl)-N-phenylamino]biphenyl (NPB, 50-x nm) as an HTL with various mixed layer thicknesses (x = 0, 10, 20, 30, 40, and 50 nm); N, N'-dicarbazolyl-3,5-benzene (mCP, 10 nm) as an ECL; iridium(III)bis[(4,6-di-fluoropheny)-pyridinato-N,$C_2$] picolinate (FIrpic, 8 wt%) doped with both mCP (20 nm) single host and mCP 1,3,5-tris(N-phenylbenzimidazole-2-yl)benzene (TPBi) partial mixed host (1:1, 10 nm) as an EML; TPBi (40 nm) as an ETL; Liq (2 nm) as an electron injection layer; and Al (100 nm). The device structure and energy level diagram are shown in Fig. 1, and all devices were fabricated considering suitability for purpose [13,14].

## 3. Results and discussion

Devices A and B were fabricated to confirm RZ extension when the mixed layer located the RZ. Device A is a reference device, which has no mixed layer but a typical blue PHOLED. Therefore, an additional device was fabricated according to the location of RZ in the basic structure.