

# Efficiency control of organic light-emitting diode for high contrast ratio performance in active matrix display applications



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## ABSTRACT

We demonstrate the possibility of controlling organic light-emitting diodes (OLEDs) efficiency with an optimized hole-delay layer (HDL) in order to achieve very high contrast ratio needed for active matrix display applications. No triplet exciton confinement structure and a molybdenum trioxide (MoO<sub>3</sub>) HDL at ITO/hole transport layer interface were used for a careful placing and adjusting of the exciton recombination zone. An optimized thickness of 50 nm thick MoO<sub>3</sub> allows to cut off the efficiency at the black level of active matrix driving mode while it gets greater at higher luminance at high current density region over 20 mA/cm<sup>2</sup> compared to conventional device. Our suggested efficiency control way is believed to be very useful to future active matrix OLED displays.

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## 1. Introduction

Organic light-emitting diodes (OLEDs) have attracted considerable attention because of their potential applicability to flat-panel displays [1–3], backlighting, and candidates for the next generation lighting, [4,5] owing to wide viewing angle, low driving voltage, thin, light-weight, and possibly also flexible displays. An essential requirement for display applications is to have high contrast ratio (CR) because it directly relates to image quality. The CR of display can be defined by two different ways as following equations:

$$CR = L_w / L_b, \text{ ambient CR} = (L_w + L_{ar}) / (L_b + L_{ar}),$$

where  $L_w$  and  $L_b$  are the luminescence at white and black states and  $L_{ar}$  is the luminescence from ambient reflection. For OLED display applications both CRs should be high enough. Fortunately, in terms of CR, OLED is ideal display due to its theoretically infinite CR because it could realize true black. Therefore, main studies focus on improving ambient CR by reducing the incoming ambient light: black cathodes and absorbing layers as integral solutions, anti-

reflection coatings and circular polarizers as external solutions are the main developed solutions [6].

The OLED efficiency has been recently improved thanks to phosphorescent materials for active matrix OLED (AMOLED) applications because it directly relates to device power consumption. However, too high efficiency generates undesired problem in the practical device applications. For example, too high efficiency originated by phosphorescent OLED materials produces unwanted light emission in the off-state of AMOLED display. Hence, important contrast ratio (CR) performance in AMOLED applications declines seriously. Generally low temperature polysilicon (LTPS) thin film transistors (TFTs) are used for sub-pixel red, green, and blue OLED current controls. Off-state current levels of these transistors at the off-state gate voltage (about  $-5$  V) are generally about  $\sim 10$  pA ranges [7]. About  $5 \times 10^{-4}$  mA/cm<sup>2</sup> current density is applied to each sub-pixel of  $\sim 2000 \mu\text{m}^2$  size, thus leading to undesirable light emission, resulting to a serious CR decrease of AMOLEDs [8]. Among sub-pixel red, green, and blue colors, green has the highest current efficiency (cd/A) values because human eye sensitivity of green color is high. When green phosphorescent materials are used, this CR become quite small ( $\leq 100:1$ ).

In this study, we present an intrinsic way to obtain a high CR by designing the OLED structure itself and by trying to reduce the off-state luminance term ( $L_b$ ) value. We demonstrate a way to control and adjust the efficiency trend in order to achieve very low

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luminous efficiency at low current density while keeping high efficiency at higher luminance.

## 2. Experimental

N,N'-Bis(naphthalen-1-yl)-N,N'-bis(phenyl)benzidine (NPB) from Duksan Hi-Metal and 4,4'4''-tris(N-carbazoyl)-triphenylamine (TCTA) from Luminescence Technology were used as hole injection layer (HIL) and electron blocking layer (EBL), respectively, to make efficient green PHOLEDs. 4,4'-N,N'-dicarbazole-biphenyl (CBP) from Daejoo Electronic Materials and (Ir(ppy)<sub>3</sub>) from Gracel (now Dow Chemical company) were used as a host and green phosphorescent dopant material, respectively. Bphen (4,7-diphenyl-1,10-phenanthroline) was purchased from Acros Organics and used as hole blocking layer (HBL). LG201 from LG Chemical (proprietary material available for purchase from LG Chemical) and 8-hydroxyquinolinolato-lithium (Liq) were used as mixed electron transporting layer (ETL). Thin Liq was also used as electron injection layer (EIL). Molybdenum trioxide (MoO<sub>3</sub>) from Kojundo Chemical Laboratory was used to delay hole injection. To fabricate green PHOLED devices, we cleaned the ITO glass by using sonification in an isopropylalcohol and acetone. Then, we rinsed it using deionized water, and finally we treated UV-ozone treatment. All organic materials were deposited on the pre-cleaned ITO glass as anode by using the vacuum evaporation technique under a pressure of  $\sim 10^{-7}$  Torr. The deposition rate of all organic layers including HTL, EBL, emissive layer (EML), HBL, and ETL was about 0.5 Å/s. Aluminum (Al) was deposited in another vacuum deposition system without breaking vacuum. A deposition rate of Al was 6 Å/s. The current density–voltage ( $J$ – $V$ ) and luminance–voltage ( $L$ – $V$ ) data of PHOLEDs were measured by Keithley SMU 2635A and Minolta CS-100A, respectively. The OLED area was 4 mm<sup>2</sup> for all the

samples studied in this work. Electroluminescence (EL) spectra and CIE coordinate were obtained using a Minolta CS-1000A.

## 3. Results and discussion

We firstly fabricated a conventional bottom-emitting green phosphorescent device (Device 1) with the following structure: ITO/NPB (40 nm)/TCTA (10 nm)/CBP:Ir(ppy)<sub>3</sub> (5%, 20 nm)/Bphen (5 nm)/LG201:Liq (1:1, 30 nm)/Liq (1.5 nm)/Al (100 nm) [9]. This structure, designed to confine triplet excitons in the EML, is commonly used to achieve highly efficient devices [10]. Higher triplet energy of Bphen (T1 2.5 eV) than Ir(ppy)<sub>3</sub> (2.4 eV) [11] can avoid triplet exciton quenching by low triplet energies of mixed ETL. The triplet energies of LG201 (2.4 eV) and Liq (2.2 eV) are lower than that of Ir(ppy)<sub>3</sub>. The triplet energies of these two mixed ETL materials were confirmed by density functional theory molecular simulation method [12]. The HBL consisting in 5 nm thick Bphen and the EBL consisting in 10 nm thick TCTA along with the hole-type EML of 20 nm thickness CBP lead to a good triplet excitons confinement in the EML. Current density and luminance vs. applied voltage ( $J$ - $V$ - $L$ ) characteristics of Device 1 indeed show good performances with a turn-on voltage of 2.9 V (at 1 cd/m<sup>2</sup>) and a driving voltage of 4.9 V (at 1000 cd/m<sup>2</sup>) [Fig. 2a]. Also cd/A vs.  $J$  characteristic of Device 1 [Fig. 3] shows an overall high efficiency, reaching a maximum of 51.0 cd/A at 424 cd/m<sup>2</sup>. But the efficiency at low current density is also too high (37.9 cd/A at  $5 \times 10^{-4}$  mA/cm<sup>2</sup>) to generate black light emission at the TFT off-state.

Thus we designed and fabricated a second device (Device 2), removing the Bphen HBL, with the following structure: ITO/NPB (40 nm)/TCTA (10 nm)/CBP:Ir(ppy)<sub>3</sub> (5%, 20 nm)/LG201:Liq (1:1, 30 nm)/Liq (1.5 nm)/Al (100 nm). In this case, lower triplet energy mixed ETL than phosphorescent dopant can generate excitons

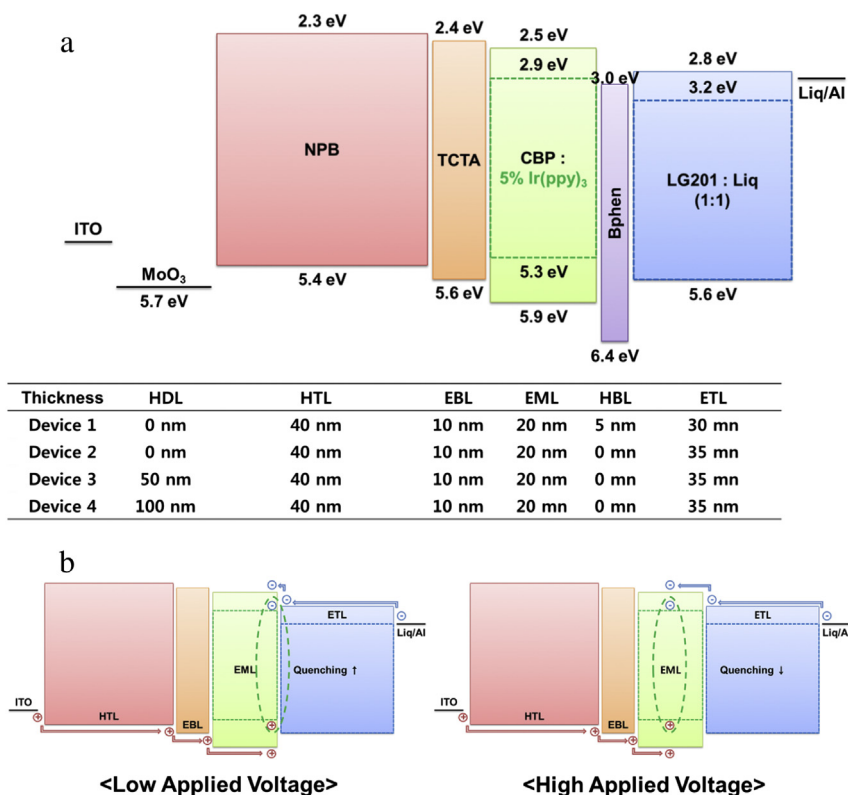


Fig. 1. (a) Energy band diagrams of fabricated green phosphorescent devices and (b) exciton recombination zone shift scheme with applied voltage. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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