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Luminous efficiency enhancement in blue phosphorescent organic light-emitting diodes with an electron confinement layers

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ABSTRACT

This study reports the results of blue phosphorescent organic light emitting diodes (PHOLEDs) employing an electron confinement layer (ECL), tris-(phenylpyrazole)iridium ($Ir(ppz)_3$) and a hole confinement layer (HCl), 1,3,5-tris(N-phenylbenzimiazole-2-yl)benzene (TPBi). The electrical and optical characteristics of PHOLEDs with different emissive layers, including current density, luminance, and luminous efficiency, were analyzed. The thickness of the individual emissive layer was optimized, however, and the total thickness of the emitting region was kept constant at 300 Å. This work reveals that the effective electron confinement, due to a large energy level offset between the electron confinement and emitting layers, helps to improve hole–electron current balance in the emitting region. The maximum external quantum efficiency of 23.40% at 1500 cd/m^2 was achieved for PHOLEDs with an ECL, which is 60% higher than the structural identical control device without ECL.

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1. Introduction

Since the report by Tang and Van Slyke on organic light-emitting diodes (OLEDs) [1,2], OLEDs have become a popular research subject due to the advantages such as reduced power consumption, compatibility with flexible substrates, high color rendering index, high contrast and wide viewing angle. When a current is applied to the electrodes of the polarization direction, the injected electrons and holes can recombine in the organic layers to release energy by emitting light of a particular color, depending on the properties of the organic material. Since the charge transport in organic semiconductors depends on the specific processes of "hopping" between molecules more or less isolated along the chain of the polymers, the conductivity of the organic semiconductors is several orders of magnitude lower than that of inorganic counterparts. Phosphorescent organic light-emitting diodes (PHOLEDs) have also attracted a worldwide attention for application in flat panel displays and solid-state lighting [3–7]. Many progresses have been made in improving the performance of PHOLEDs. For example, the use of a solution-processed gold nanoparticle-based interlayer between the anode and the hole-injection layer was shown to enhance emission efficiency and reduce efficiency roll-off in PHOLEDs [8], and improved electroluminescence (EL) emission and color stability of transparent white PHOLEDs with a weak angular-dependent emission were accomplished by avoidance of the overlap between the resonant wavelength and the peak wavelengths of the emitters [9].

However, improving the performance of blue PHOLEDs still remains an open challenge [10–12]. Various methods have been developed to optimize the performance of blue PHOLED [13], including realizing hole–electron balance in the emissive layer (EML) [14], designing a better surface texture for improving external quantum efficiency [15], and reducing efficiency roll-off in PHOLEDs at ultrahigh current densities by suppression of triplet-polaron quenching [16].

Among various methods for higher efficiency, the electron confining structures have proved to be an effective approach for better device performance [17,18], by confining charge carriers and exciton within the each emitting layer. Thus the charge carrier recombination efficiency and exciton formation probability can be beneficially enhanced [19]. The organic molecules were insufficiently restricted by Van der Waals force among molecules in the organic quantum-well. In fact, quantum well structures leading

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to carrier confinement have been proved to achieve better device performance such as high luminous efficiency, [20], tunable EL zone [21], and carrier balance resulting in the enhanced exciton creations in the emitting region [22–25].

In this study, an enhanced electron–hole current balance in blue PHOLEDs was realized by introducing an ECL structure in EML. Emissive materials and ECL material have different HOMO–LUMO energy levels. The location of an ECL in emissive region in the PHOLEDs were investigated and optimized to achieve the best device performance. The effect of ECL on external quantum efficiency and current density–voltage–luminance (*J–V–L*) characteristics was analyzed and compared to that of HCl.

2. Experiment

Indium tin oxide (ITO) coated glass substrates with a sheet resistance of ~12 Ω/sq were used for device preparation. The ITO glass was cleaned in an ultrasonic bath sequentially with deionized water, isopropyl alcohol, acetone, deionize water and isopropyl alcohol. Thereafter, the pre-cleaned ITO glass was treated with O_2 plasma at 5.0×10^{-2} Torr, 100 W for 2 min. All organic materials were deposited by thermal evaporation under a pressure of $\sim 1.0 \times 10^{-7}$ Torr. The PHOLEDs were encapsulated in a glove box with O_2 and H_2O levels below 1 ppm. A barium-oxide powder desiccant was used to improve the operation lifetime of the encapsulated PHOLEDs. Current density–voltage (*J–V*) characteristics of the PHOLEDs were measured with a source measure unit (Keithley 238) with the DC voltage bias. Optical and EL properties of the PHOLEDs such as luminance, luminous efficiency (LE), Commission International de L'Eclairage (CIE) coordinates and EL spectra were analyzed by spectroradiometer (LMS PR-650 spectrophotometer).

Fig. 1 shows the molecular structures of organic materials used in the blue PHOLEDs. The blue PHOLEDs composed of a 4,4′-cyclohexylidenebis [N,N-bis(4-methylphenyl)benzenamine] (TAPC) hole transport layer (HTL), an EML, a 1,3,5-tris(N-phenylb enzimiazole-2-yl)benzene (TPBi) electron transport layer (ETL), an 8-Hydroxyquinolinolato-lithium (Liq) electron injection layer (EIL) and an aluminum (Al) cathode. A layer of bis[2-(4,6-difluoro phenyl)pyridinato-C2,N](picolinato)iridium(III)(FIrpic)-doped 1,3-bis(N-carbazolyl) benzene (mCP) was used as the EML, and thin layers of Ir(ppz)3 and TPBi were employed as the ECL and HCl, respectively. Since the injection of electrons into a TAPC layer causes irreversible defect sites leading to electromer emission and low efficiency [26], TAPC is not suitable for ECL. Therefore, Ir(ppz)3 was chosen as ECL in device C and device E.

The layer configuration of different blue PHOLEDs, devices A, B, C, D and E, is summarized in Table 1.

Table 1
Layer structure of blue PHOLEDs.

Device	Layer structure
Device A	ITO (1800 Å)/TAPC (600 Å)/mcp: Firpic–8% (300 Å)/TPBi (300 Å)/Liq (20 Å)/Al (1200 Å)
Device B	ITO (1800 Å)/TAPC (600 Å)/mcp: Firpic–8% (150 Å)/TPBi (15 Å)/mcp: Firpic–8% (150 Å) TPBi (300 Å)/Liq (20 Å)/Al (1200 Å)
Device C	ITO (1800 Å)/TAPC (600 Å)/mcp: Firpic–8% (150 Å)/Ir(ppz)$_3$ (15 Å)/mcp: Firpic–8% (150 Å) TPBi (300 Å)/Liq (20 Å)/Al (1200 Å)
Device D	ITO (1800 Å)/TAPC (600 Å)/mcp: Firpic–8% (100 Å)/TPBi (15 Å)/mcp: Firpic–8% (100 Å)/TPBi (15 Å)/mcp: Firpic–8% (100 Å)/TPBi (300 Å)/Liq (20 Å)/Al (1200 Å)
Device E	ITO (1800 Å)/TAPC (600 Å)/mcp: Firpic–8% (100 Å)/Ir(ppz)$_3$ (15 Å)/mcp: Firpic–8% (100 Å)/Ir(ppz)$_3$ (15 Å)/mcp: Firpic–8% (100 Å)/TPBi (300 Å)/Liq (20 Å)/Al (1200 Å)

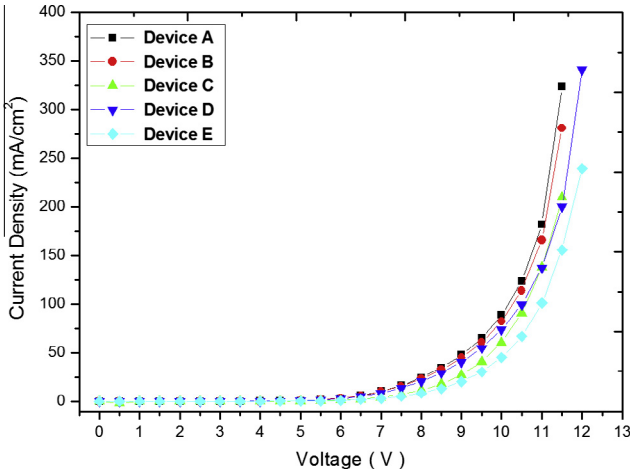

Fig. 2. Current density–voltage characteristics of blue PHOLEDs.

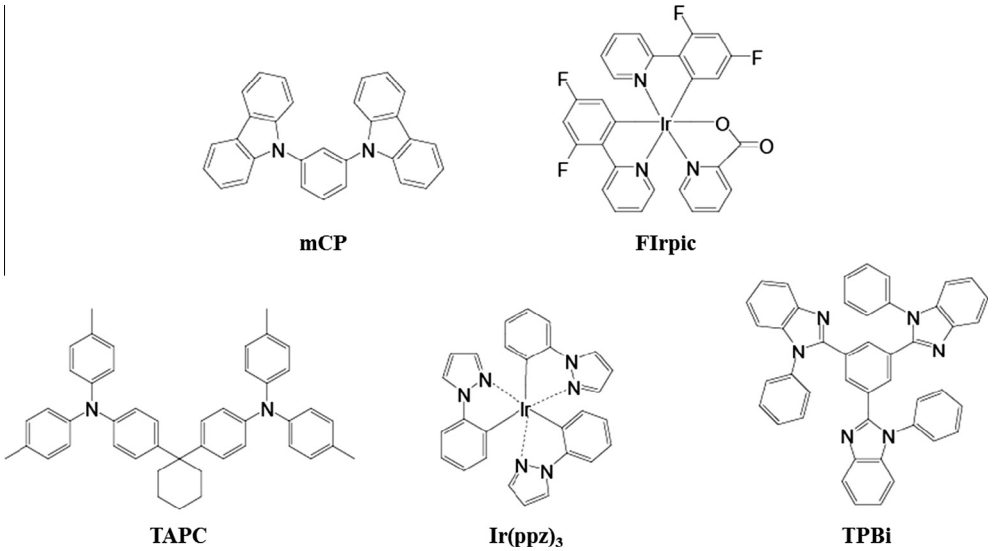

Fig. 1. Molecular structures of organic materials used in the blue PHOLEDs.

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