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Hybrid white organic light-emitting diodes with improved color stability and negligible efficiency roll-off based on blue fluorescence and yellow phosphorescence

Xuehui Wang^{a,1}, Shiming Zhang^{a,b,1}, Ziyang Liu^a, Shouzhen Yue^a, Zhensong Zhang^a, Yu Chen^a, Guohua Xie^c, Qin Xue^d, Yi Zhao^{a,*}, Shiyong Liu^a

^a State Key laboratory on Integrated Optoelectronics, College of Electronic Science and Engineering, Jilin University, Changchun 130012, People's Republic of China

^b Département of Chemical Engineering, École Polytechnique de Montréal, Montréal, Québec, Canada H3C3J7

^c Institut für Angewandte Photophysik, Technische Universität Dresden, 01062 Dresden, Germany

^d College of Physical Science and Technology, Central China Normal University, Wuhan 430079, People's Republic of China

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ABSTRACT

We report hybrid white organic light-emitting diodes (WOLEDs) based on yellow phosphorescence of Iridium (III) bis(4-phenylthieno[3,2-c]pyridinato-*N*, *C*²)acetylacetonate (PO-01) and blue fluorescence of *p*-bis(*p*-*N,N*-diphenyl-amino-styryl) benzene (DSA-Ph). By introducing appropriate thickness of tris(phenylpyrazole) Iridium [Ir(ppz)₃] as interlayer between the adjacent emission layers, taking advantage of the assistance electron-transporting behavior of guest molecules, efficient WOLEDs with negligible efficiency roll-off and high color stability are obtained. The best device shows a peak current efficiency of 21.0 cd/A at 2,300 cd/m² and the value can be maintained as high as 20.1 cd/A at 9,300 cd/m². Furthermore, the Commission Internationale de L'Eclairage coordinate of the corresponding device only changes marginally from (0.41, 0.46) to (0.40, 0.46) over 10³–10⁴ cd/m².

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1. Introduction

White organic light-emitting diodes (WOLEDs) have drawn tremendous attention and are expected to dominate the next-generation flat-panel display and solid-state lighting due to their merits of ultra-thin, light weight, and environmental friendliness [1,2]. In terms of materials, nowadays, phosphorescent material is extensively adopted to obtain high efficiency OLEDs due to its potential for achieving 100% internal quantum efficiency [3]. However, up to now, high efficiency blue phosphor with acceptable operational lifetime still has not been developed, which limits the developing of all-phosphor OLEDs [4]. In recent years, WOLEDs which combine blue fluorescent with red (or yellow) phosphorescent emitters (hybrid WOLED) have been designed [5], and the hybrid WOLEDs can indeed show improved operational stability [6]. In addition, for practical lighting purpose, WOLEDs also need to offer high efficiency as well as stable performance over a wide working-luminance range [7–9]. Therefore, the study of high efficiency hybrid WOLEDs with excellent stability is indispensable.

In this paper, we fabricated hybrid WOLEDs using yellow phosphorescence Iridium (III) bis(4-phenylthieno[3,2-c]pyridinato-*N*, *C*²)acetylacetonate (PO-01) and blue fluorescence 2-methyl-9,10-di(2-naphthyl) anthracene (MADN): *p*-bis(*p*-*N,N*-diphenyl-amino-styryl) benzene (DSA-Ph) based on different device architectures. By introducing appropriate thickness of tris(phenylpyrazole) Iridium [Ir(ppz)₃] as interlayer between the adjacent blue emission layer (B-EML) and yellow EML (Y-EML), utilizing DSA-Ph as well as PO-01 molecules as assistance electron-transporting channels, devices with negligible efficiency roll-off and high color stability are achieved. The best device shows a peak current efficiency (CE) of 21.0 cd/A at 2,300 cd/m² and the value can be maintained as high as 20.1 cd/A at 9,300 cd/m², besides, the Commission Internationale de L'Eclairage (CIE) coordinate of the corresponding device only changes marginally from (0.41, 0.46) to (0.40, 0.46) over 10³–10⁴ cd/m².

2. Experimental details

The glass coated with a layer of indium tin oxide (ITO) with a sheet resistance of 20 Ω/square was adopted as the substrate for OLEDs. Prior to film deposition, the substrates were cleaned by scrubbing and sonication, and then treated with oxygen plasma for 10 min to enhance the surface work function of ITO anode. All organic layers were deposited under high vacuum (< 4 × 10⁻⁶ Torr). 4,4,4-tris(3-methylphenylphenylamino)-triphenylamine (*m*-MTDATA) and

* Corresponding author. Tel.: +86 431 85168242 8301; fax: +86 431 85168270.

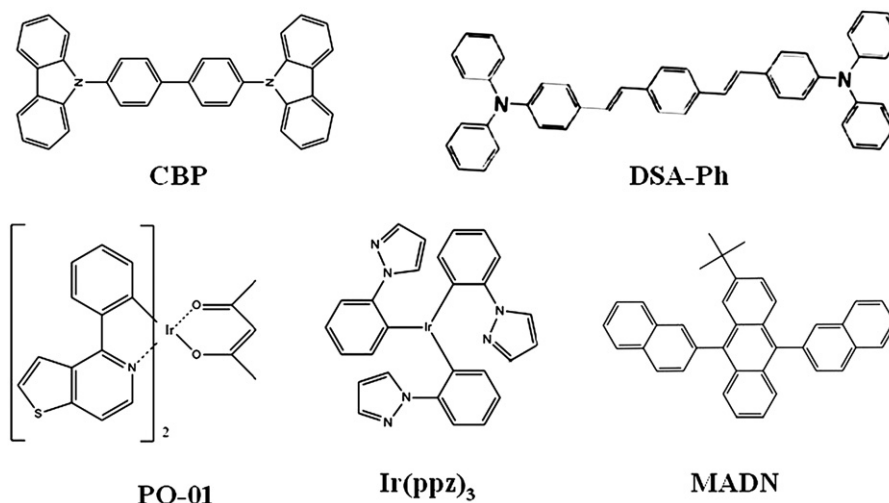
E-mail address: yizhao@jlu.edu.cn (Y. Zhao).

¹ These authors contributed equally to this work.

7-diphenyl-1,10-phenanthroline (BPhen), serve as hole-transporting layer (HTL), and electron-transporting layer (ETL), respectively. Ir(ppz)₃ was served as interlayer, 4, 4'-N,N-dicarbazole-biphenyl (CBP) served as the host for PO-01. After deposition of LiF, the samples were transferred to metal chamber, which resulted in a vacuum break due to the change of the shadow masks to determine the active area. The thermal deposition rates were 0.1, 0.05, and 0.5 nm/s for organic materials, LiF, and Al, respectively. The thicknesses of these deposited layers and the evaporation rate of individual material were monitored in situ using an oscillating quartz thickness monitor. The active area of the device was 4 mm². Molecular structural formulas of some of the materials used in the OLEDs are shown in Scheme 1. The electroluminescent (EL) spectra and CIE coordinates of the devices were measured by a PR650 spectroscan spectrometer, and the current (*I*)-voltage (*V*)-luminance characteristics were recorded simultaneously by combining the spectrometer with Keithley model 2400 programmable voltage-current source. The efficiency calculation method the device is the same as S.R. Forrest's group by assuming the emissive profiles of the device as the Lambertian emitter's [10]. All measurements were carried out at room temperature under ambient conditions.

3. Results and discussions

We first demonstrated two sets of devices as follows and the corresponding configurations are shown in Fig. 1(a) and (b).



Scheme 1. Molecular structures of some materials used in this study.

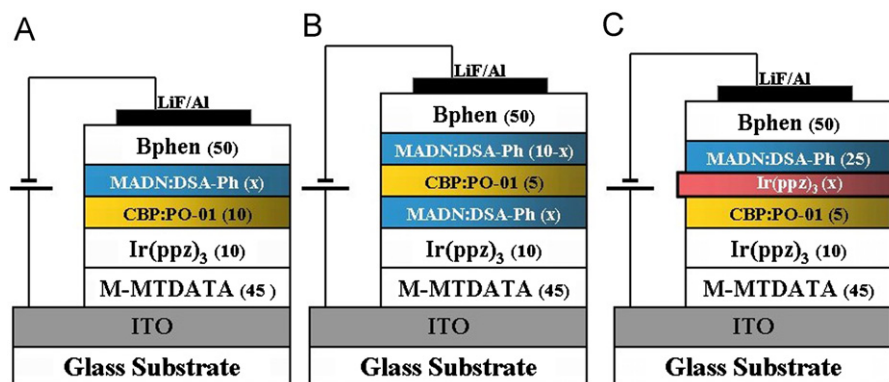


Fig. 1. Schematic layer stack of the investigated OLEDs.

A-series: ITO/*m*-MTDATA (45 nm)/Ir(ppz)₃ (10 nm)/CBP: PO-01 (10 nm, 6 wt%)/MADN: DSA-Ph (*x* nm, 5 wt%)/BPhen (50 nm)/LiF (1 nm)/Al (100 nm), *x*=10, 15, 20 and 25 for devices A₁, A₂, A₃ and A₄, respectively.

B-series: ITO/*m*-MTDATA (45 nm)/Ir(ppz)₃ (10 nm)/MADN: DSA-Ph (*x* nm, 5 wt%)/CBP: PO-01 (5 nm, 6 wt%)/MADN: DSA-Ph (10-*x* nm, 5 wt%)/BPhen (50 nm)/LiF (1 nm)/Al (100 nm), *x*=2, 3, 4 and 5 for devices B₁, B₂, B₃ and B₄, respectively.

The normalized EL spectra of A-series devices at different applied voltages are illustrated in Fig. 2. We can see all devices show a PO-01 dominated EL emission. Besides, interestingly, despite the B-EML thickness increases from A₁ to A₄, the blue emission with respect to yellow emission (ratio of the photons from DSA-Ph and PO-01: *R*_{B/Y}) was observed to decrease contrarily. In order to reveal the reason for this unusual phenomenon, electron-only and hole-only devices were fabricated and tested as shown in Fig. 3. We can see from Fig. 3 that an obvious increase in electron mobility can be observed upon doping DSA-Ph into MADN, which indicates that DSA-Ph serves as a transporting-channel for electrons, whereas DSA-Ph in MADN has almost no influence on hole-transporting. Hence, the increase in B-EML will prevent more holes from transporting to the B-EML/BPhen interface than electrons to the Y-EML/Ir(ppz)₃ interface. In this case, more holes will be used for PO-01 emission, resulting in a decrease in the *R*_{B/Y} value inevitably.

Fig. 4(a) and (b) shows the CE versus luminance curves of devices A and B. Unfortunately, although B-series devices emit better white color, they exhibit a rather low CE value compared with A-series.

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