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Improved efficiency in blue phosphorescent organic light-emitting diodes by the stepwise doping structure

Liping Yang [a], Xiaoping Wang [a, b], Zhiqi Kou [a, *], Changyan Ji [a]

[a] College of Science, University of Shanghai for Science and Technology, Shanghai, China
[b] Shanghai Key Lab of Modern Optical System, Shanghai, China

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ABSTRACT

The electro-optical properties of the blue phosphorescent organic light-emitting diodes (PHOLEDs) can be affected by the stepwise doping structure in the emitting layer (EML). A series of multi-EML devices with different doping concentration of blue dopant (FIrpic) are fabricated. The effect of the stepwise doping structure close to the electron transport layer is more obvious than that close to the hole transport layer. When the doping concentration increases gradually from the hole injection side to the electron injection side, the maximum values of the luminance, current and power efficiency can reach to 9745 cd/m^2 (at 9 V), 32.0 cd/A and 25.1 lm/W in the device with the asymmetric tri-EML structure, which is improved by about 10% compared with that in the bi-EML device. When the number of the EML is four, the performance of the device becomes worse because of the interface effect resulting from different concentration of dopant.

1. Introduction

Organic light-emitting diode (OLED) has shown strong potential in the next generation of display and lighting applications due to many advantages such as flexibility, short response time, low driving voltage, low power consumption and wide viewing angle [1,2]. Phosphorescent organic light-emitting diodes (PHOLEDs) are highly efficient because that both singlet and triplet excitons can be harvested for light emission [3,4]. High efficiency and luminance of green and red PHOLEDs have been reported for industrial applications, whereas the color purity, efficiency and stability of blue PHOLEDs have yet to be improved for realization in the commercial market [5,6]. The electroluminescence (EL) mechanisms can be categorized into energy transfer from the host to dopant, or carrier trapping at the dopant sites [7,8]. Many researches working on blue PHOLEDs focus on metal organic complexes material such as iridium(III) bis[(4,6-difluorophenyl)-pyridinato-N,C2′)] picolinate (FIrpic) [9–11]. Some structures have been proposed in order to improve the efficiency and stability of blue PHOLEDs, such as using multi-layer structure [12,13], quantum well structure [14,15], or inserting exciton blocking layer between the transport layer and the emitting layer (EML) [16,17]. In general, the charge carrier transporting property can be affected by the doping concentrate profile and charge carrier-trapping site. A stepwise doping structure can control charge carrier transport and recombination balance well through effective electron injection. Recently, Kim et al. demonstrated the blue PHOLED with the highest doping concentration as part of the EML close to an electron transport layer (ETL) showed a maximum current efficiency of 20.74 cd/A [18]. Chu et al. also noted that electron injection and transport can be enhanced by increasing doping ratio at the EML close to the ETL, the maximum power efficiency can reach to be 13.3 l m/W, which is almost 40% improved compared with that of the conventional device [19]. The studies have not been investigated for stepwise doping profile within EML based on the asymmetric EML device.

In the present work, we investigate asymmetric EML devices with stepwise doping profile in order to further improve the efficiency. The influence of stepwise doping structure in the blue PHOLEDs will be discussed under the same total thickness of EML. A series of multi-EML devices with different doping concentration of blue dopant (FIrpic) are fabricated. Firstly, the arrangement of doping concentration gradient change is studied, it is found that the performance is better when the doping concentration near ETL is higher than that near the hole transport layer (HTL) in the bi-EML device. Secondly, the effect of the stepwise doping structure close to ETL side is more obvious than that close to HTL side when EML is further separated into the asymmetric tri-EML device. Thirdly, the

* Corresponding author.
E-mail address: usst102@aliyun.com (Z. Kou).

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more EMLs, the more difficult carrier injection, so the performance becomes worse in the four-EML device. So the most optimized device is the kind of asymmetric tri-EML structure.

2. Experimental

All the devices are fabricated by vacuum deposition under a base pressure lower than 5×10^{-5} Pa without breaking the vacuum. The substrate is a glass sheet which is coated with indium tin-oxide (ITO). The sheet resistance is 15 Ω/sq. Before deposition, the substrates are cleaned by ultrasonic bath for 15 minimums in each of the following: detergent, deionized water, propanol. All organic materials except the dopant (FIrpic) are deposited on the substrates at a rate of 1 Å/s. The stepwise doping structure can be realized by changing the ratio of growth speed between the host and dopant material for every sub-EML. And the metal cathodes (Al) are deposited at a rate of 2 Å/s. The deposition rate and film thickness are monitored by quartz crystal oscillators. The EL spectra and luminance characteristic are measured by a PR655 spectrometer. The current density and voltage are obtained and measured by a Keithley 2400 digital power.

All devices use FIrpic as blue dopant and *N*,*N*'-dicarbazolyl-3,5-benzene (mCP) as host material in EML, the average concentration of doping is 8%, the total thickness of EML is 30 nm. 4,4′,4′-tris(*N*-carbazolyl)triphenylamine (TCTA) and 1,3,5-tri(*m*-pyrid-3-yl-phenyl)benzene (TmPyPB) is chosen as the exciton blocking layer (EBL) due to their high triplet energy of 2.79 eV and 2.78 eV as show in Fig. 2 [20,21], respectively. The HTL and ETL are 1,1-bis(di-4-tolylaminophenyl)cyclohexane (TAPC) and 4,7-diphenyl-1,10-phenanthroline (Bphen), respectively. 1,4,5,8,9,11-hexaazatriphenylene-hexacarbonitrile (HAT-CN) and 8-hydroxyquinolinolato lithium (Liq) are used as the hole injection layer (HIL) and electron injection layer (EIL), respectively. The basic device structure is: ITO (100 nm)/HAT-CN (10 nm)/TAPC (20 nm)/TCTA (20 nm)/EML 1 (15 nm)/EML 2 (15 nm)/TmPyPB (10 nm)/Bphen (30 nm)/Liq (2 nm)/Al (100 nm). For devices A1 and A2, the doping concentration of EML 1 and EML 2 are 12% and 4%, 4% and 12%, respectively. Devices A3 and A4 can be obtained by separating EML 1 into two parts uniformly based on the device A2. Devices B1 and B2 can be obtained by separating EML 2 into two parts uniformly based on the device A2. When both EML 1 and EML 2 are uniformly separated into two parts simultaneously based on device A2, device C1 can be obtained. Fig. 1 shows the schematic diagrams of the EML in devices A, B and C. The insert diagram in Fig. 1 shows the molecular structures of mCP and FIrpic.

3. Results and discussion

Fig. 2 shows the schematic structure of the fabricated devices and energy level diagram of the used materials (inside brackets: triplet energy of materials). Table 1 lists the EL characteristic values of the devices tested with different structures. Fig. 3(a) shows the curves of current density and luminance vs voltage in devices A1, A2, A3 and A4. The luminance of devices A1, A2, A3 and A4 are 6021 cd/m^2, 8793 cd/m^2, 8613 cd/m^2, and 8337 cd/m^2 at 9 V, respectively. Fig. 3(b) shows the curves of current efficiency and

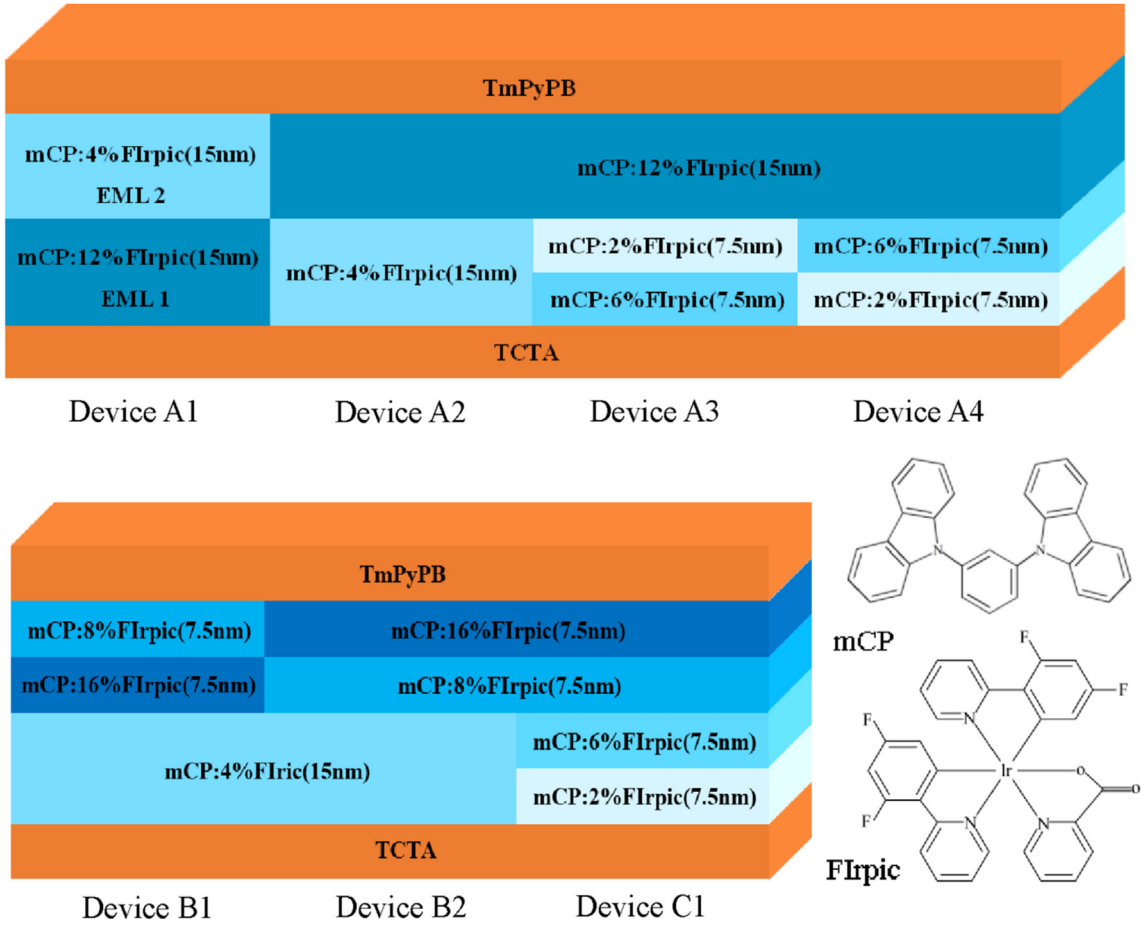

Fig. 1. Schematic diagrams of the EML in devices A, B and C. The insert diagram shows the molecular structures of mCP and FIrpic.