Optical Materials 52 (2016) 181–185

Contents lists available at ScienceDirect

Optical Materials

journal homepage: www.elsevier.com/locate/optmat

Confinement of holes and electrons in blue organic light-emitting diodes with additional red emissive layers

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ARTICLE INFO

Article history:
Received 1 November 2015
Received in revised form 27 November 2015
Accepted 17 December 2015
Available online 29 December 2015

Keywords:
Blue phosphorescent OLED
Double dopant
Luminous efficiency
External quantum efficiency

ABSTRACT

We used various emissive layer (EML) structures with ultrathin red EMLs to enhance the charge carrier balance and carrier recombination rate in blue PHOLED devices. These EML materials have different energy gaps between highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) energy levels. The ultrathin red EMLs, which were inserted in between the blue EMLs, effectively confined the charge carriers in EML, and increased the carrier recombination rate. The thickness of the individual EML was optimized, under 30 nm of the total thickness of EML. The blue PHOLEDs with ultrathin red EMLs achieved a luminous efficiency of 19.24 cd/A, which was 28.7% higher than those without ultrathin red EMLs, and the maximum external quantum efficiency was 11.81% at 500 cd/m^2.

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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 PHOLEDs [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 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 optimizing OLED performance, finding optimum doping concentration of host-dopant emitting system is required [26]. Radiative transitions involve the absorption, if the transition occurs

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http://dx.doi.org/10.1016/j.optmat.2015.12.026
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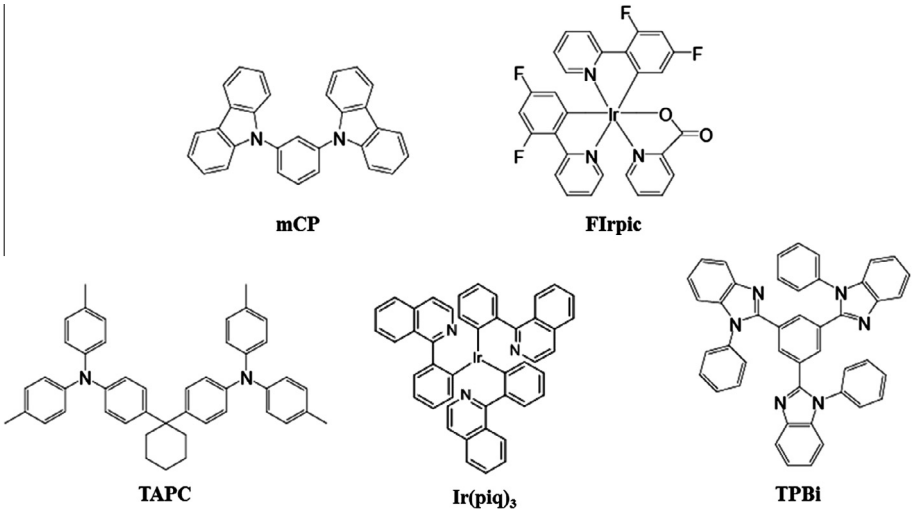

Fig. 1. Molecular structures of organic materials used in the blue PHOLEDs.

Table 1
Layer structure of different PHOLEDs.

Device	Layer structure
Device A	ITO (180 nm)/TAPC (60 nm)/mCP: FIrpic–8% (30 nm)/TPBi (30 nm)/Liq (2 nm)/Al (120 nm)
Device B	ITO (180 nm)/TAPC (60 nm)/mCP: FIrpic–8% (15 nm)/mCP: Ir(piq)$_3$ (1.5 nm)/mCP: FIrpic–8% (15 nm)/TPBi (30 nm)/Liq (2 nm)/Al (120 nm)
Device C	ITO (180 nm)/TAPC (60 nm)/mCP: FIrpic–8% (10 nm)/mCP: Ir(piq)$_3$ (1.5 nm)/mCP: FIrpic–8% (10 nm) mCP: Ir(piq)$_3$ (1.5 nm)/mCP: FIrpic–8% (10 nm)/ TPBi (30 nm)/Liq (2 nm)/Al (120 nm)
Device D	ITO (180 nm)/TAPC (60 nm)/mCP: FIrpic–8% (7.5 nm)/mCP: Ir(piq)$_3$ (1.5 nm)/mCP: FIrpic–8% (7.5 nm)/mCP: Ir(piq)$_3$ (1.5 nm)/mCP: FIrpic–8% (7.5 nm)/ mCP: Ir(piq)$_3$ (1.5 nm)/mCP: FIrpic–8% (7.5 nm)/TPBi (30 nm)/Liq (2 nm)/Al (120 nm)

to a higher energy level, or the emission, in the reverse case, of a photon. Nonradiative transitions arise through several different mechanisms, all differently labeled. A first type of relaxation of the excited state to its lowest vibrational level is called vibrational relaxation. This process involves the dissipation of energy from the molecule to its surroundings, and thus it cannot occur for isolated molecules. A second type of nonradiative transition is internal conversion (IC), which occurs when a vibrational state of an electronically excited state can couple to a vibrational state of a lower electronic state. A third type is intersystem crossing (ISC); this is a transition to a state with a different spin multiplicity. In molecules with large spin–orbit coupling, intersystem crossing is much more important than in molecules that exhibit only small spin–orbit coupling. This type of nonradiative transition can give rise to phosphorescence.

When electricity is applied, excited electron and hole pairs are transferred to the highly emissive and stable dopant side. Thus, the possibility of non-radiative decay is minimized and the operational stability is improved [27]. The energy transfer could occur through the interaction between an excitation of the donor, D^*, and a ground-state of acceptor, A, which turns into an excited state as shown by equation.

$$D^* + A \rightarrow D + A^*$$

Based on the equation, the exciton formation in a dopant molecule could result from the Förster energy transfer or Dexter energy transfer of an exciton formed in the host to the dopant molecule. Thus, there are two different mechanisms that can activate the energy transfer. Förster energy transfer is facilitated by a Coulombic interaction between the HTL or ETL bound exciton.

In this study, we used ultrathin red EMLs to achieve a high charge balance and demonstrated high-efficiency blue phosphorescent OLEDs. By doping phosphorescent emitters in the hole and electron transporting hosts as double emitting layer structure, it shows a significant improvement in device efficiency.

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

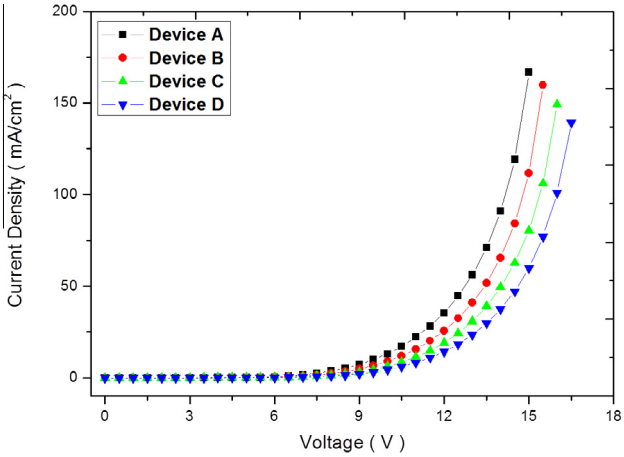

Fig. 2. Current density – voltage characteristics of blue PHOLEDs.

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