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Low driving voltage white organic light-emitting diodes with high efficiency and low efficiency roll-off

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ABSTRACT

Single emission layer white organic light-emitting diodes (WOLEDs) showing high color stability, low turn-on voltage, high efficiency and low efficiency roll-off by incorporating iridium(III) bis[(4,6-difluo-rophenyl)-pyridinato-N,C2] (FIrpic) and bis(2-phenylbenzothiazolato) (acetylacetonate)iridium(III) ($Ir(BT)_2(acac)$) phosphors dyes have been demonstrated. Our WOLEDs without any out-coupling schemes as well as n-doping strategies show low operating voltages, low turn-on voltage (defined for voltage to obtain a luminance of 1 cd/m^2) of 2.35 V, 79.2 cd/m^2 at 2.6 V, 940.5 cd/m^2 at 3.0 V and 10 300 cd/m^2 at 4.0 V, respectively, and achieve a current efficiency of 40.5 cd/A, a power efficiency of 42.6 lm/W at a practical brightness of 1000 cd/m^2, and a low efficiency roll-off 14.7% calculated from the maximum efficiency value to that of 5000 cd/m^2. Such improved properties are attributed to phosphors assisted carriers transport for achieving charge carrier balance in the single light-emitting layer (EML). Meanwhile the host–guest energy transfer and direct exciton formation process are two parallel pathways serve to channel the overall excitons to dopants, greatly reduced the unfavorable energy losses.

1. Introduction

Since the pioneering works by Ma [1] and Forrest [2] et al., phosphorescent organic light-emitting diodes (PHOLEDs) have attracted intensive attention due to their bright future of practical and commercialization. PHOLEDs with their ideal characteristics, such as the potential 100% internal quantum efficiency [3–8], have potential application for energy-efficiency flat-panel displays and promising candidates for the next generation of solid-state lighting [9–13]. White light can be realized by mixing red, green, and blue (RGB, the three primary colors) lights or by mixing two complementary colors, such as sky blue and orange lights. And it is considered that phosphorescent white organic light-emitting diodes (PHWOLED) based on complementary sky blue and orange phosphors is one of the most cost-effective methods to achieve white light emitters aiming for mass production, as the simplified PHWOLEDs configurations would be of significant advantage for high volume fabrication associated with potential general lighting and display applications.

After decades of research and development, WOLEDs with power efficiency (PE) beyond 100 lm/W with outcoupling technology and 30 lm/W without outcoupling technology have been achieved [11]. Nevertheless, high-efficiency WOLEDs with low operating voltages are still a great challenge [5,14–23]. It is worth mentioning that reducing the operating voltage is crucially important to improve the power efficiency and ensure the compatibility with the common low voltage active matrix driver circuitry for portable applications. Although the efforts are taken in organizing the optoelectronic properties of

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the WOLED by function integration, only few of them can realized the high electroluminescence (EL) efficiencies, such as external quantum efficiency (EQE) over 10% and power efficiency (PE) more than 20 lm/W, accompanied with the low driving voltages (e.g. <3 V for onset and <4 V at 100 cd/m^2 for portable display) [24–27]. Toward this end, we fabricated PHWOLEDs by combining sky blue with orange phosphors. The materials iridium(III) bis[(4,6-difluo-rophenyl)-pyridinato-N,C2] (FIrpic) and bis(2-phenylbenzothiazolato) (acetylacetonate)iridium(III) (Ir(BT)$_2$(acac)) were selected to display broad emission covering as much of the visible light spectrum as possible and generate white light, and 4,6-Bis(diphenylphosphoryl) dibenzothiophene (DBTDPO) [36] was selected as a common host. We have demonstrated low driving voltage PHWOLED (2.6 V for 79.2 cd/m^2, 3.0 V for 940.5 cd/m^2 and 4 V for 10300 cd/m^2), high efficiency (EQE of 14.3% and PE of 42.6 lm/W at about 1000 cd/m^2), and low efficiency roll-off (13% for EQE from 1000 cd/m^2 to 5000 cd/m^2), which is one of the best reports for PHWOLED [28–31]. This contribution demonstrates that the low driving voltages and high efficiencies can be simultaneously realized in the single emission layer WOLEDs.

2. Experimental

Fig. 1a shows the proposed energy diagram of the fabricated PHWOLEDs. In which both FIrpic and Ir(BT)$_2$(acac) are co-doped into a common host material DBTDPO served as emission layer (EML), which is sandwiched between the electrons/excitons blocking layer (EBL) of fac-tris(1-phenylpyrazolato,N,C2) (Ir(ppz)$_3$) and the electron transport layer (ETL) of 4,7-diphenyl-1,10-phenanthroline served (BPhen). What is more, molybdenum oxide (MoO_x)-doped 4, 4′, 4″-tris(3-methylphenylphenylamino) triphenylamine (m-MTDATA) and neat m-MTDATA are introduced as hole transport layer (HTL), and MoO_x and Cs_2CO_3 are served as anode/cathode buffer layer for hole/electron injection. The lowest unoccupied molecular orbital (LUMO) positions, highest occupied molecular orbital (HOMO) positions, and triplet levels of the materials we used are plotted in Fig. 1.

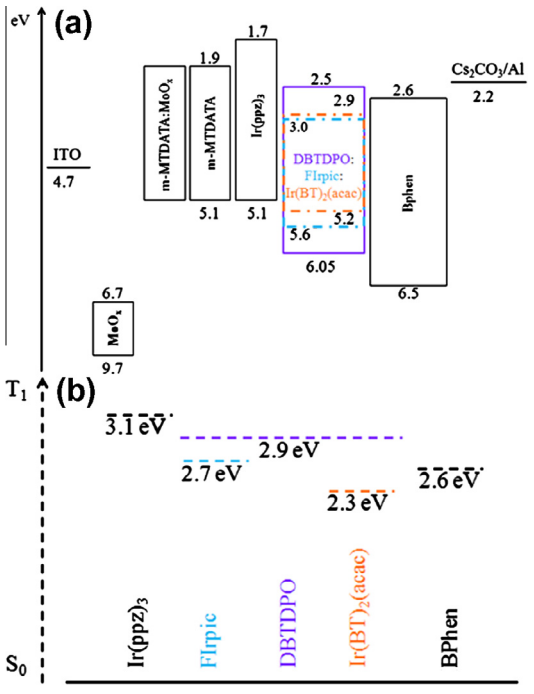

Fig. 1. (a) Schematic diagram of HOMO–LUMO values of some materials used in this paper. (b) Triplet energy levels of the materials. The values are obtained from the literature. [8,32–36].

Prior to the device fabrication, the patterned ITO-coated glass substrates were scrubbed and sonicated consecutively with acetone, ethanol, and de-ionized water, respectively. All the organic layers were thermally deposited in vacuum ($\sim 4.0 \times 10^{-4}$ Pa) at a rate of 1–2 Å/s monitored in situ with the quartz oscillator. After the deposition of Cs_2CO_3, the samples were transferred to metal chamber under a nitrogen atmosphere. The electroluminescence (EL) spectra are measured by a PR655 spectroscan spectrometer. The luminance-current density–voltage characteristics are recorded simultaneously with the measurement of the EL spectra by combining the spectrometer with a Keithley model 2400 programmable voltage–current source. All measurements are carried out under atmospheric environments.

3. Results and discussion

DBTDPO has a high T_1 of 2.90 eV which facilitate the exothermic energy transfer to the dopants (shown in Fig. 1b). However, the energy barriers between the HOMOs of EML and the EBL is larger than the energy between the LUMOs of EML and ETL, the hole injection from typical organic hole transport layers Ir(ppz)$_3$ HOMO into DBTDPO HOMO is more difficult than electron injection from BPhen LUMO into DBTDPO LUMO. Meanwhile DBTDPO contains two phosphine oxide groups directly bonded to the dibenzothiophene shows excellent electron transporting characteristic which is in favor of the transporting electrons in the EML [36]. Therefore we expect the imbalanced carrier-injection/transporting in the EML and masses of excitons locate at the interface of EML and EBL, nonradiative excitons quenching processes, such as triplet–triplet excitons annihilation (TTA) and triplet-polaron annihilation (TPA) processes, and/or field-induced quenching will accelerate efficiency roll-off of phosphorescent devices at high current densities [37–39].

Since the major carrier in the DBTDPO host devices is electron[36] and Ir^{3+} complexes often have strong hole/electron-capture ability or hole/electron-assisted transport ability, [30,31,40,41] the moderately manipulate carrier transportation in the host may facilitate the charge balance in EMLs. In this case, the carrier transporting ability of the host should be modulated finely by introducing the phosphors of Ir^{3+} complexes. To clarify the effect of phosphors-doped DBTDPO on electrical properties, the hole-only and electron-only devices were fabricated with the configurations of ITO|MoO_x (2 nm)|m-MTDATA:MoO_x (15 wt.%, 30 nm)|m-MTDATA (10 nm)|Ir(ppz)$_3$ (10 nm)|