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Efficient single-emitting layer hybrid white organic light-emitting diodes with low efficiency roll-off, stable color and extremely high luminance

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ABSTRACT

An efficient single-emitting layer hybrid white organic light-emitting diode (WOLED) was developed, simultaneously fulfilling low efficiency roll-off, stable color and extreme luminance. At the practical luminance of 1000 cd/m^2, a total current efficiency of 42.8 cd/A and power efficiency of 19.2 lm/W are achieved, maintaining as high as 40.5 cd/A and 15.5 lm/W even at 5000 cd/m^2. Besides, a slight color variation [(0.025, 0.011)] and extreme luminance ($\sim 10^6$ cd/m^2) are obtained. The working mechanism is unveiled and it is demonstrated that the triplet-exciton-confining ability of electron transport layers plays a more vital role in device performances, particularly for the lifetime.

Introduction

Nowadays, white organic light-emitting diodes (WOLEDs) are approaching mainstream display markets and also being aggressively explored for the next-generation lighting applications due to their extraordinary characteristics, such as high efficiency, low power consumption and flexibility [1]. In general, three kinds of WOLEDs are reported according to the employed emitting materials, such as all-phosphorescent WOLEDs, all-fluorescent WOLEDs and hybrid WOLEDs which are based on hybrid (flourescent (F) and phosphorescent (P)) emitters schemes [2]. Since P emitters enable an internal efficiency up to 100%, converting both singlet and triplet excitons into photons, which corresponds to a fourfold increase in efficiency compared to that achievable in singlet-harvesting F emitters (except delayed fluorescence), the use of P materials is essential to boost the efficiency [3]. However, there is no proper blue P material in terms of lifetime and color-stability so far, limiting the development of all-phosphorescent WOLEDs [4]. To alleviate this difficulty, hybrid WOLEDs, which combine stable F blue emitters with efficient P green–red/orange emitters, are considered to be a desirable solution, owing to their merits, high efficiency, stable color and long lifetime [5].

Sun et al. took the first step to realize highly efficient hybrid WOLEDs via the combination of stacked F-interlayer (IL)–P–P–IL–F emitters, achieving a maximum total power efficiency (PE) of 37.6 lm/W and 23.8 lm/W at 500 cd/m^2 [2]. This smart device can harvest both singlet and triplet excitons along completely independent channels and hence nearly resonant energy transfer from the conductive host to dopants for both the singlet and triplet energy (T_1) can be realized. Meanwhile, the exchange energy losses (0.8 eV) originating from intersystem crossing from the host singlet into a blue phosphor triplet state are eliminated, further enhancing the efficiency [2]. However, the structure is somewhat complicated and the efficiency roll-off is serious.

To simplify the device structures, hybrid WOLEDs with P–IL–F emitters have steadily attracted researcher's interest, since they only need two EMLs (one F blue EML and one P green–red/orange EML) to furnish white light. As a matter of fact, a large number of efforts have been devoted to the pursuit of this fascinating approach. For example, Wong et al. built a WOLED based on the

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P–IL–F structure by utilizing a heteroleptic orange Ir-complex, obtaining a maximum efficiency of 13.5 lm/W and 7.8 lm/W at 1000 cd/m^2 [6a]. Ma et al. described the P–IL–F concept by combining orange-phosphorescence with blue-fluorescence, yielding a maximum PE of 24.9 lm/W and 13.5 lm/W at 1000 cd/m^2 [6b]. We have reported WOLEDs with the P–IL–F schemes via an investigation and optimization of each organic layer, performing a maximum efficiency of 58.4 lm/W and 15.1 lm/W at 1000 cd/m^2 [6c].

However, since the host of P emitters, the host of F emitters and the IL are exploited different materials, the structures are not simplified enough [6]. In fact, structures can be more simplified if the P–IL–F based WOLEDs use a versatile material as both the host of emitters and the IL, which can be referred to as a single-emitting layer (SEL) structure, since only one homogeneous organic layer is contained in the emitting layer [7]. However, research work relying on such design concept is still in its infancy. Although Yang et al. reported a SEL hybrid WOLED, only 13.1 cd/A and 7 lm/W were achieved at 500 cd/m^2, only a maximum luminance of ~7500 cd/m^2 was recorded and a large color-shift $\Delta = (0.03,\ 0.07)$ was observed dring 6–8 V [8a]. Although Tan et al. carried out a SEL hybrid WOLED, only a maximum current efficiency (CE) of 15.3 cd/A, a maximum PE of 9.1 lm/W, a maximum luminance of 34,908 cd/m^2 and no color-stability were attained [8b]. From these facts, it can be concluded that the introduction of SEL structure is a pretty simplified but promising way to prepare hybrid WOLEDs. However, it is easily noted that the performance of previous SEL hybrid WOLEDs is yet unsatisfactory. Besides, the design strategy and operational working mechanism of SEL hybrid WOLEDs, which can give a guideline for further performance improvement, is not fully investigated. Moreover, although the electron transport layer (ETL) usually has a great influence on the OLEDs performances, no detailed work has been documented to study their effects on hybrid WOLEDs. Therefore, it is essential that an urgent endeavor is needed to improve SEL hybrid WOLEDs performances, although the efficiency/luminance/color-stability/efficiency roll-off trade-off can be scarcely accomplished in simplified structures so far.

In this paper, we have developed a highly efficient SEL hybrid WOLED, which uses 4,4–*N*,*N*-dicarbazolebiphenyl (CBP) as both the host of emitters (orange phosphor and blue fluorophore) and the IL, simultaneously fulfilling low efficiency roll-off, stable color and extremely high luminance. At the practical luminance of 1000 cd/m^2, a total CE of 42.8 cd/A and PE of 19.2 lm/W can be achieved, representing the highest level in SEL hybrid WOLEDs. Besides, the device exhibits a maximum total CE of 42.8 cd/A and PE of 21.1 lm/W during a large range of luminance, which slightly decrease to 40.5 cd/A and 15.5 lm/W even at a high luminance of 5000 cd/m^2, indicating that the efficiency roll-off is rather low. In addition, a slight Commission Internationale de L'Eclairage (CIE) coordinates variation of (0.025, 0.011) is observed, indicating that the device exhibits an excellent color-stability. Moreover, a luminance of 97,067 cd/m^2 is obtained, which is the highest among hybrid WOLEDs in the literature so far, to the best of our knowledge. Finally, it is demonstrated that the triplet-exciton-confining ability of electron transport materials plays a more vital role in hybrid WOELDs performances, particularly for the lifetime. Such superior results will be helpful for the rational design of both material and device structure for high-performance WOLEDs.

Experimental

Fig. 1 depicts the studied hybrid WOLEDs with the configuration of ITO/MeO-TPD: F4-TCNQ (100 nm, 4%)/NPB (15 nm)/CBP: $(MPPZ)_2Ir(acac)$ (25 nm, 8.5%)/CBP (4 nm)/CBP: DSA-ph (20 nm, 3%)/ETLs (30 nm)/LiF (1 nm)/Al (200 nm), where ITO is indium tin oxide, MeO-TPD is *N*,*N*,*N*′,*N*′- tetrakis(4-methoxyphenyl)-benzidine, F4-TCNQ is tetrafluoro-tetracyanoqino dimethane, NPB is *N*,*N*′-di(naphthalene-1-yl)-*N*,*N*′-diphenyl-benzidine, F material *p*-bis(*p*-*N*,*N*-di-phenyl-aminostyryl) benzene (DSA-ph) is a blue guest, P material iridium (III) diazine complexes $(MPPZ)_2Ir(acac)$ is an orange guest and ETLs include 2,2′,2″-(1,3,5-benzinetriyl)-tris(1-phenyl-1-*H*-benzimidazole) (TPBi) and 4,7-diphenyl-1,10-phenanthroline (Bphen). The detailed fabrication and measurement of devices followed well-established processes as reported elsewhere [9].

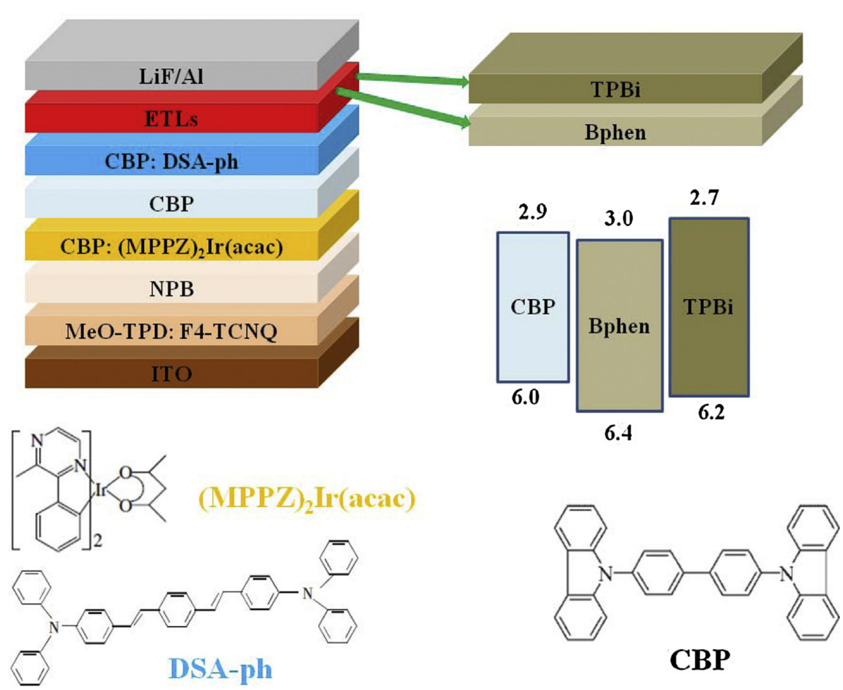

Fig. 1. Top: schematic layer structure of the WOLEDs and proposed energy-levels. Bottom: the chemical structure of emitters and CBP.