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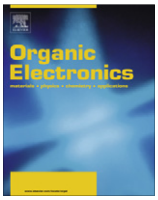

Host engineering for improving the performance of blue phosphorescent organic light-emitting devices

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ABSTRACT

We report an effective means to greatly improve the performance of blue phosphorescent organic light-emitting devices by doping well-known electron- or hole-transporting triplet host material, specifically, 3-(4-biphenyl)-4-phenyl-5-(4-*tert*-butylphenyl)-1,2,4-triazole (TAZ) or 4,4′,4″-tris(*N*-carbazolyl)triphenylamine (TCTA), into emissive layer to form mixed host structures. A superior device performance with high current and power efficiencies of 47.4 cd/A and 37.3 lm/W, respectively, and more importantly, a theoretical maximum of external quantum efficiency of 21.9%, can be achieved for an optimized TCTA-doped device. On the other hand, doping of TAZ into hole-transporting host material would degrade device performance. It is found that, in addition to the well-known effects of charge carrier balance, both energy levels and triplet energies of mixed host materials play crucial roles in determining the device performance. As confirmed by the time-resolved phosphorescence decay studies, the lifetime of FIrpic is strongly dependent on the triplet energy of host materials and the shorter lifetime of triplet excitons with high Stern–Volmer quenching constant of 0.1564%$^{-1}$ in TAZ-doped films is the origin of the low electroluminescence efficiency of the TAZ-doped devices.

1. Introduction

Phosphorescent organic light-emitting devices (PHOLEDs) are enjoying enormous interest over the last two decades, because of their potential for effective use of both singlet and triplet excitons to achieve 100% internal quantum efficiency. In designing an efficient PHOLED, the use of a good host material with suitable triplet energy (E_T) is of equal importance with the development of phosphorescent guests [1–3]. Practically, the E_T of the host material and the adjacent charge transporting materials should be greater than that of the phosphorescent guest to ensure exothermic energy transfer and a good exciton confinement within the emissive layer (EML). Many smart device configurations, including the use of dual EMLs, metal-doped electron-transporting layers, and utilization of tandem structures, and high-performance host materials [1–6] have recently been developed to improve the efficiencies of PHOLEDs. Indeed, red and green PHOLEDs with peak external quantum efficiencies (EQE) up to 21.6% and 23.5% [7,8], respectively, have been successfully demonstrated.

On the other hand, it is not a simple task to design host materials with suitably high E_T (>2.7 eV) and bipolar transport properties for blue phosphorescent guests. Generally, it is an inherent tradeoff between the E_T and the electrical bandgap, i.e. the energy difference between the lowest unoccupied molecular orbital (LUMO) level and the highest occupied molecular orbital (HOMO) level [9]. A high E_T inevitably signifies a large electrical bandgap that impedes the carrier injection from adjacent electron- (or hole-) transporting materials into the EML and thus increases the driving voltage of blue PHOLEDs. In addition, a restriction in the length of π-electron conjugation in the host

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molecules in order to maintain a high E_T results in a reduction of the carrier transporting properties [6]. Particularly, most of the host materials with high E_T, i.e. carbazole-containing compounds or aromatic phosphine oxides, are unipolar in nature. As charge balance plays an important role in determining the device efficiency, this ultimately limits the device efficiency and leads to a detrimental efficiency roll-off at high current densities owing to triplet–triplet annihilation [10].

Until very recently, Lee et al. reported an effective approach to increase the charge transporting property in EML [11,12]. Through the incorporation of hole-transporting host material into the electron-transporting EML to form a mixed triplet host system, the EQE of blue PHOLEDs can be dramatically increased up to 20.5%, doubling that of single host device (8.96%) [12]. The enhanced EQE is mainly due to the improvement on charge carrier transport balance as well as a broader recombination zone within the EML. This finding opens up the possibility to further improve the performance of PHOLEDs where the doping approach might be applicable for other commonly used host materials.

In this letter, we present the utilization of mixed triplet host systems to improve device performance and reduce the power consumption of blue PHOLEDs; particularly, either an electron-transporting or a hole-transporting triplet host material was intentionally doped into the commonly used *N*,*N*′-dicarbazolyl-3,5-benzene (mCP) host to form mixed triplet host system. We found that the device efficiency is very sensitive to the energy levels and the relative composition of the host materials in the EML, in which a superior device performance with high current and power efficiencies of 47.4 cd/A and 37.3 lm/W, respectively, can be obtained for an optimized device. Particularly, device efficiencies are strongly dependent on the choice of triplet host materials, as suggested by time-resolved phosphorescence decay studies for different mixed host thin films.

2. Experimental

Patterned indium-tin-oxide (ITO)-coated glass substrates (30 Ω/square) were cleaned with Decon 90, rinsed in deionized water, then dried in an oven, and finally treated in an ultraviolet-ozone chamber. PHOLEDs were fabricated with a hole-transporting α-naphthylphenylbiphenyl diamine (NPB) layer, a carrier confinement 4,4′,4″-tris(*N*-carbazolyl)triphenylamine (TCTA) layer, and an electron-transporting bis(2-methyl-8-quinolinato)-4-phenylphenolate aluminum(III) (BAlq) layer. Devices with the configuration of ITO/NPB (70 nm)/TCTA (5 nm) (30 nm)/EML (30 nm)/BAlq (30 nm)/LiF (0.8 nm)/Al (200 nm) were fabricated, in which either TCTA or 3-(4-biphenyl)-4-phenyl-5-(4-*tert*-butylphenyl)-1,2,4-triazole (TAZ) was doped into mCP to form mixed host system as EML. Six percent of bis [2-(4′,6′-difluorophenyl)pyridinato-*N*,$C^{2'}$]iridium(III) (FIrpic) was doped into EML as phosphorescent guest. In particular, TCTA and TAZ are well-known hole-transporting and electron-transporting materials, respectively; while mCP is hole-transporting triplet host material. For comparison, a standard device with 6% FIrpic:mCP as EML was also made as reference. Fig. 1 shows the proposed energy level diagram for the devices, in which HOMO, LUMO levels, and E_T of the organic materials are taken from the literature [1,13,14]. All organic materials were used as purchased and the films are sequentially deposited by thermal evaporation in high vacuum chamber without vacuum break. A shadow mask was used to define the cathode and to make four 0.1 cm^2 devices on each substrate. The deposition rates were controlled by a quartz oscillating thickness monitor to be 1–2 Å/s for the organic materials and metals. The current density–voltage–luminance (*J*–*V*–*L*) characteristics and electroluminescence (EL) spectra were measured simultaneously with a programmable Keithley model 2420 power source and a Photoresearch PR655 colorimeter. All measurements were carried out in air at room temperature.

Time-resolved photoluminescence decay measurements were performed using a conventional laser system. The excitation source used was a 355-nm output (third harmonic) of a Spectra-Physics Quanta-Ray Q-switched GCR-150-10 pulsed Nd-YAG laser. Luminescence decay signals were detected by a Hamamatsu R928 PMT and recorded on a Tektronix Model TDS-620A (500 MHz, 2 GS/s) digital oscilloscope and analyzed using a program for exponential fits.

3. Results and discussion

Fig. 2(a) depicts the EL spectra for devices doped with various TAZ concentrations to form mixed hosts. Apparently, for the reference device (i.e. 0% TAZ), it exhibits a characteristic FIrpic emission peaking at 472 and 496 nm in the absence of any undesirable emission from adjacent hole- or electron-transporting layers. This confirms that

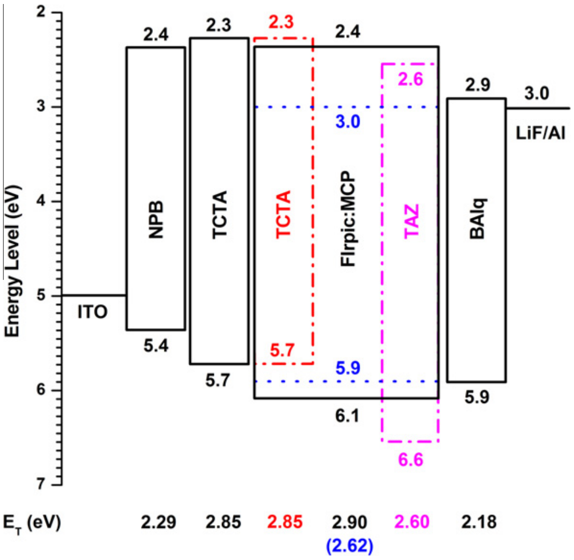

Fig. 1. Proposed energy level diagram for the devices. Note that numbers indicate the respective HOMO and LUMO energies relative to the vacuum as well as the E_T in eV. HOMO and LUMO energies of FIrpic are also indicated with dotted lines; while E_T of FIrpic is shown in parentheses.