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Highly Efficient Green Phosphorescent Organic Light Emitting Diodes with Improved Efficiency Roll-Off

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Abstract. A 10-nm thick 4,4',4"-tris(carbazole-9-yl)tri-phenylamine (TcTa) interlayer effectively confines triplet excitons within the emissive layer (EML) of phosphorescent organic light emitting diodes (PHOLEDs) based on green-emitting $Ir(ppy)_3$ dopant and improves the charge balance in the EML of the device, resulting the higher device efficiencies of 61.7 cd/A, 19.7 %, and 43.2 lm/W with the maximum luminance of 75,310 cd/m^2 and highly improved efficiency roll-off (22.2% at 20 mA/cm^2) when compared to those (61.1 cd/A, 19.6 %, and 47.2 lm/W with a maximum luminance of 38,350 cd/m^2) of the standard device with efficiency roll-off of 62.3 % at 20 mA/cm^2.

Keywords: Organic semiconductors; Electronic devices; OLEDs;
PACS: 81.05.Fb; 85.65.+h; 85.60.Jb; 85.60.Pg:

INTRODUCTION

The potential use of organic light emitting diodes (OLEDs) in lighting and display applications has attracted enormous attention of researchers worldwide in the recent decades. The phosphorescent OLEDs (PHOLEDs) show much higher performance When compared to that of fluorescent OLEDs because of both singlet and triplet excitons can be harvested for the light emission in the device [1-2]. The phosphorescent iridium(III) dopant, fac-tris(2-phenylpyridine)-iridium [$Ir(ppy)_3$], with higher photoluminescence (PL) quantum efficiency is the most commonly used green emitter in the PHOLEDs, exhibiting the higher device efficiencies beyond the theoretical limit [3]. In order to avoid triplet-triplet annihilation in highly efficient PHOLEDs, $Ir(ppy)_3$ is doped in (4,4′-N, N′-dicarbazole) biphenyl (CBP) host which transfers its singlet and triplet exciton energy to the dopant emitter to efficiently harvest all excitons for the light emission [4]. The higher device efficiencies have been achieved by balanced injection of charge carriers and the effective confinement of charge carriers and/or excitons formed within the emissive layer (EML) of the device. In this study, we use widely used 4,4'-bis[N-(1-nathyl)-N-phenyl-amino]biphenyl (NPB) as hole transport layer (HTL), 4,4',4"-tris(carbazole-9-yl)tri-phenylamine (TcTa) as exciton blocking layer (EBL), and Bathocuproine(2,9-dimethyl-4,7-diphenyl-1,10-phenanthroline) (Bphen) as electron transport layer (ETL) in the PHOLEDs based on $Ir(ppy)_3$ doped in CBP host as EML. We present the significance of TcTa EBL in highly efficient PHOLEDs with widely used, relatively low-cost charge transporting and host materials.

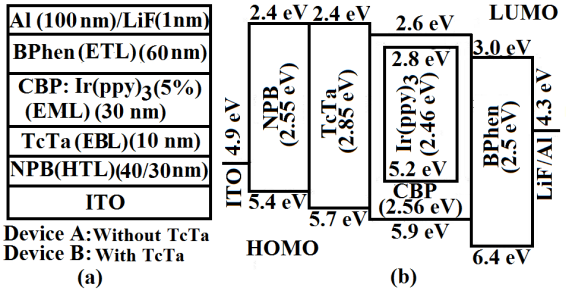

FIGURE 1. (a) The device structure and (b) energy level diagram of the materials used in the devices.

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DEVICE FABRICATION

The PHOLEDs were fabricated using the following device structure: Indium-tin-oxide (ITO)/NPB HTL (40 nm for device A and 30 nm for device B)/ TcTa EBL (10 nm for device B)/CBP host doped with $Ir(ppy)_3$ dopant (5%) as EML (30 nm)/Bphen ETL (60 nm)/LiF (1 nm)/Al (100 nm) as shown in Fig. 1(a). Device A without TcTa EBL is fabricated as standard device. The patterned ITO (anode) coated glass substrates were ultrasonically cleaned in acetone for 10 min followed by isopropyl alcohol, dried in each step at 90 ºC for 10 min and UV treated for 10 min before loading into the deposition chamber for the device fabrication. All organic layers were deposited by thermal evaporation process under a vacuum of ~5 x 10^{-6} Torr and LiF as electron injection layer and Al cathode were deposited without breaking the chamber vacuum. The fabricated devices were transferred into the glove-box for the encapsulation of the devices with moisture getter using UV curable epoxy. The electroluminescence spectra of the devices are recorded at a driving current of 10 mA/cm^2 using Minolta CS-1000. The current density-voltage-luminance (*J-V-L*) characteristics of the devices were measured using the current/voltage source measure unit (Keithley 238) and Minolta CS-1000 under ambient condition.

RESULTS AND DISCUSSION

Device A was fabricated using relatively low-cost charge transporting and host materials with the device structure of NPB HTL (LUMO: 2.4 eV, HOMO: 5.4 eV)/CBP host (LUMO: 2.6 eV, HOMO: 5.9 eV) doped with $Ir(ppy)_3$(5%) /BPhen ETL (LUMO: 3.0 eV, HOMO: 6.4 eV) [2]. The energy level diagram of the materials used in the devices is shown in Fig. 1(b). The current density – voltage - luminescence (*J-V-L*) characteristics of devices A and B are shown in Fig. 2.

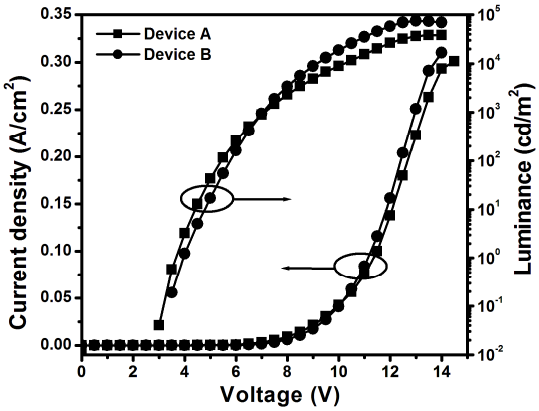

FIGURE 2. The *J-V-L* characteristics of the devices.

From *J-V-L* characteristics of the device A, the device showed the turn-on voltage (defined as an applied voltage required for the luminance of 1 cd/m^2) of 3.5 V with drive voltages of 5.5 V for 100 cd/m^2, 7 V for 1000 cd/m^2 and 10.5 V for 10,000 cd/m^2. Device A exhibits the maximum luminance of 38,350 cd/m^2 at 13.5 V. The electroluminescence (EL) spectra of the devices recorded at a driving current of 10 mA/cm^2 are shown in Fig. 3. The device A showed the electroluminescence (EL) emission peak at 512 nm with shoulder peak at 539 nm with CIE color coordinates of (0.28, 0.60), confirming the green emission from the triplet excited states of the phosphorescent $Ir(ppy)_3$ dopant emitter [5-7]. A residue emission around 450 nm was observed in the EL spectrum of the device A (Inset of Fig. 3), which is attributed to the NPB emission due to the diffusion of electrons and/or triplet excitons from EML to NPB HTL having the small energy barrier of 0.2 eV for the electrons at the NPB/EML interface and the lower triplet energy (T_1) level of 2.56 eV when compared to that (T_1 = 2.56 eV) of CBP host [3]. Fig. 4 shows the current efficiency (η_c, cd/A) and external quantum efficiency (η_{ext}, %) characteristics of the devices A and B. The device A showed the maximum η_c of 61.1 cd/A, η_{ext} of 19.6 %, and the power efficiency (η_p) of 51.8 lm/W. Device A showed the efficiency roll-off of 46.4% at 1 mA/cm^2, 62.3 % at 20 mA/cm^2, and 66.7 % at 100 mA/cm^2.

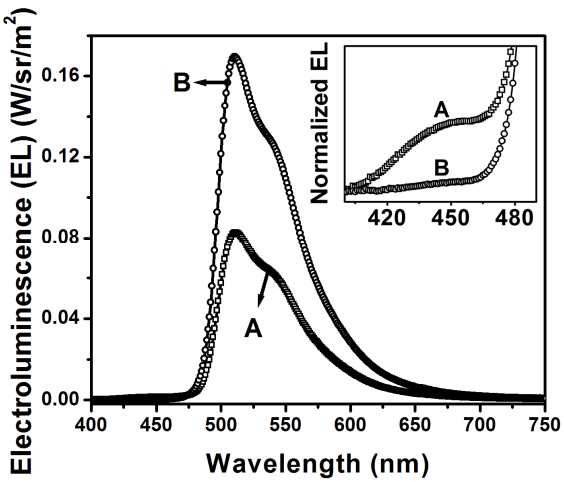

FIGURE 3. EL spectra of devices A and B. Inset shows the normalized EL spectra of the devices.

In order to suppress the diffusion of electrons and/or excitons from EML to NPB HTL, a 10-nm thick TcTa (LUMO: 2.4 eV, HOMO: 5.7 eV) having the higher T_1 energy level of 2.85 eV (NPB: 2.55 eV, CBP: 2.56 eV) is inserted between NPB HTL and EML in the device A to obtain the device B. From the J-V-L characteristics of the device B, it exhibits the turn-on voltage of 4 V with the drive voltages of 5.5 V for 100 cd/m^2, 7 V for 1000 cd/m^2 and 9 V for 10,000

cd/m^2. Device B shows the maximum luminance of 75,310 cd/m^2 at 13 V. The increased energy barrier by 0.2 eV at EBL/EML interface for hole injection resulted in the increased turn-on voltage of the device B. The device B showed no change in the EL emission of the dopant at 512 nm with shoulder peak at 539 nm with CIE color coordinates of (0.28, 0.61) as observed in the device A. TcTa interlayer in the device B effectively blocks the diffusion of triplet excitons from EML to NPB HTL due to its higher triplet energy level of 2.85 eV (NPB: 2.55 eV; CBP: 2.56 eV), resulting the complete suppression of residue NPB emission at around 450 nm. No emission from the CBP host (at 390 nm) and/or adjacent charger transporting layers indicates the effective confinement of charge carriers and/or excitons and the complete energy transfer from CBP host to Ir(ppy)$_3$ dopant emitter in the EML of the device B. The device B showed the maximum η_c of 61.7 cd/A, η_{ext} of 19.7 %, and the power efficiency (η_p) of 43.2 lm/W. Device B showed the highly improved efficiency roll-off of 0.02 % at 1 mA/cm^2, 22.2 % at 20 mA/cm^2, and 35.9 % at 100 mA/cm^2 when compared to those (46.3% at 1 mA/cm^2, 62.3 % at 20 mA/cm^2, and 66.7 % at 100 mA/cm^2) of the device A without TcTa. The improved efficiency roll-off of the device B at increasing current densities indicates the effective confinement of charge carriers and/or excitons and balanced charge carriers in the EML of the device.

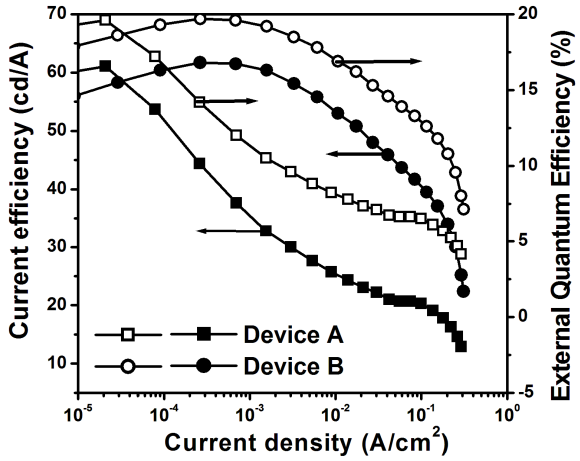

FIGURE 4. The η_c-η_{ext} characteristics of the devices.

The hole transporting type TcTa serves as an efficient exciton blocking layer (EBL) in the green PHOLEDs based on the phosphorescent Ir(ppy)$_3$ dopant emitter due to its higher triplet energy level (2.85 eV) for the effective confinement of charge carriers and/or excitons within the EML of the device exhibiting the higher device efficiencies. It also improves the chare balance in the EML of the device, resulting in highly improved efficiency roll-off at increased current densities. These results show that this type of highly efficient green-emitting PHOLEDs would be useful for the low cost lighting and display applications.

CONCLUSION

The efficient green PHOLEDs based on Ir(ppy)$_3$ dopant emitter were fabricated using relatively low-cost CBP host and charge transporting layers, NPB, TcTa and BPhen, for cost effective device applications. Device exhibits the green emission at 512 nm with CIE color coordinates of (0.28, 0.61). A 10-nm thick hole transporting type TcTa interlayer effectively confines the charge carriers and/or excitons and improves the charge balance in the EML of the device, resulting the higher device efficiencies of 61.7 cd/A, 19.7 %, and 43.2 lm/W with the maximum luminance of 75,310 cd/m^2 and highly improved efficiency roll-off (22.2 % at 20 mA/cm^2) when compared to those (61.1 cd/A, 19.6 %, and 47.2 lm/W with a maximum luminance of 38,350 cd/m^2) of the standard device with efficiency roll-off of 62.3 % at 20 mA/cm^2.

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