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Study of triplet exciton's energy transfer in white phosphorescent organic light-emitting diodes with multi-doped single emissive layer

Jin Wook Kim [a], Nam Ho Kim [a], Ju-An Yoon [a], Seung Il Yoo [a], Jin Sung Kang [a], Kok Wai Cheah [b], Fu Rong Zhu [b], Woo Young Kim [a,c,*]

[a] Department of Green Energy & Semiconductor Engineering, Hoseo University, Asan 336-795, Republic of Korea
[b] Department of Physics and Institute of Advanced Materials, Hong Kong Baptist University, Kowloon Tong, Hong Kong, China
[c] Department of Engineering Physics, McMaster University, Hamilton, Ontario L8S 4L7, Canada

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ABSTRACT

The performance of three color single emissive layer white phosphorescent organic light-emitting diodes (PHOLEDs), with different hole transporting materials of N,N′-diphenyl-N,N′-bis(l-naphthyl-phenyl)-(l,l′-biphenyl)-4,4′-diamine (NPB), 4,4_,4_-tris_N-carbazolyl_tri-Phenylamine (TCTA) and 1,1-bis[(di-4-tolylamino)phenyl]cyclohexane (TAPC), was analyzed. It is found that the luminous efficiency of white PHOLEDs is closely related to the triplet exciton energy level in the hole transporting layer (HTL). White PHOLEDs with a TAPC as HTL, having the highest triplet exciton energy level amongst the three different hole transporting materials, yielded external quantum efficiency of 25.5% at 4.5 V and a high luminous efficiency of 51 cd/A at 4.5 V with CIE color coordinates of (0.34, 0.39) at 10 V. The results reveal that the effective confinement of triplet excitons in white PHOLEDs with a high triplet exciton energy level HTL (TAPC) allows improving the luminous efficiency, as compared to the devices made with NPB and TCTA. Additionally, we demonstrated possibility for the loss of intensity in EL spectra of the white PHOLED devices with NPB and TCTA as HTL compared to that of the device with TAPC as HTL.

1. Introduction

Since Tang and Van Slyke reported on the bulk heterojunction organic light-emitting diodes (OLEDs) [1], OLEDs have gained tremendous attentions due to their applications in solid state lighting and flat-panel displays [2–5]. Phosphorescent organic light-emitting diodes (PHOLEDs) have attracted lots of interests because of their technical potential with 100% internal quantum efficiency (IQE) [6–10], achieved by harvesting both singlet and triplet excitons. However, to realize this benefit in white PHOLEDs, different device design and optimization are desired for high performance toward commercial applications [11–13]. Many progresses have been made in improving the performance of OLEDs, including high power efficiency tandem OLEDs incorporating bulk heterojunction organic bipolar charge generation layer [14], and reduced efficiency roll-off in PHOLEDs at ultrahigh current densities by suppression of triplet-polaron quenching [15]. Two color and three color (blue, green and red) white in single and multi-emissive layers have been used for producing white PHOLEDs. Tandem structures with two or three color white systems using both fluorescent and phosphorescent materials were reported. The accomplishment of bi-directional and symmetrical illumination semitransparent white PHOLEDs also offer additional features and design freedoms for application in planar diffused lighting [16–20]. White PHOLEDs using two color white single emissive layer have been extensively studied for achieving high luminous efficiency. There is only one exciton energy transfer process from dopant with higher energy level to the one with lower energy level in single emissive. In three color white PHOLEDs, the additional number of exciton energy transfer process should be considered for controlling the emissions from blue, green and red dopants. In fact, white PHOLEDs using three primary color dopants were developed in several research groups recently. However, these white PHOLEDs were doped in multi emissive layers, hybrid and tandem structures. White PHOLEDs with single emissive layer may have relatively more limited exciton recombination zone [21]. Therefore, white PHOLEDs with single emissive structure can be a favorable device configuration for achieving high efficiency.

To maximize white PHOLED efficiency using three primary color dopants (blue, green and red) in single emissive layer, how to confine triplet excitons in emissive layer (EML) should be considered. Thus, we need to use the host materials with higher

* Corresponding author at: Department of Green Energy & Semiconductor Engineering, Hoseo University, Asan 336-795, Republic of Korea.
E-mail address: wykim@hoseo.edu (W.Y. Kim).

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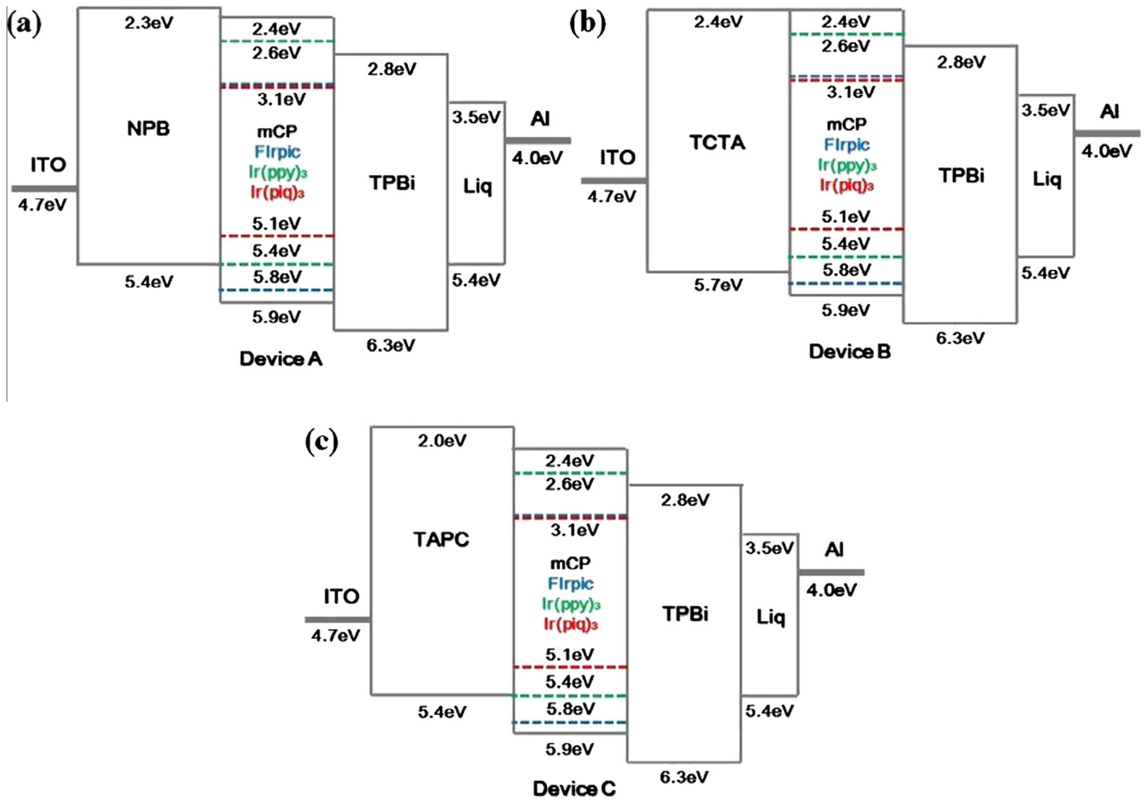

Fig. 1. Schematic energy band diagrams of white PHOLEDs with different hole transporting layers of (a) NPB (device A), (b) TCTA (device B) and (c) TAPC (device C). The corresponding energy levels of the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) of the functional materials are also listed.

triplet energy level than dopant materials to prevent reverse energy transfer to the host molecules [22,23]. In addition to the triplet excitons confinement by host molecules, triplet excitons diffusion into a hole-transport layer (HTL) and an electron transport layer (ETL) should be considered since the triplet excitons by charge carrier recombination are usually formed near such interfaces [24]. The loss of triplet excitons caused by their diffusion into HTL and/or ETL materials can decrease white PHOLEDs' efficiency. Conceivably, we believe that there are several previous papers reporting on the effect of HTL materials on the white OLED device's efficiency [25–27]. However, some complicated device structures, e.g., multiple emissive units in white OLEDs, are often employed involving complex fabrication processes and cost challenges in mass production. Therefore, we will focus on effect of properties of HTL materials in single emissive white PHOLEDs with three primary dopants which has simple structure.

In this work, effect of triplet energy level in HTL on the performance of three color single emissive layer white PHOLEDs, with a device configuration of ITO(1500 Å)/HTL(700 Å)/mCP:FIrpic-8.0%:Ir(ppy)$_3$-0.5%:Ir(piq)$_3$-0.5%(300 Å)/TPBi(300 Å)/Liq(20 Å)/Al(1200 Å), was analyzed. Different hole transporting materials of N,N′-diphenyl-N,N′-bis(l-naphthyl-phenyl)-(l,l′-biphenyl)-4,4′-diamine (NPB), 4,4_,4_-tris_N-carbazolyl_tri-Phenylamine (TCTA) and 1,1-bis[(di-4-tolylamino)phenyl]cyclohexane (TAPC) having different triplet energy levels of 2.3 eV, 2.6 eV and 2.9 eV, were used for device fabrication. We demonstrate mechanism of triplet exciton energy transfer between the three dopants in EML. And we confirm the effect of diffusion of triplet excitons from dopants to HTL materials on efficiency and electroluminescence (EL) spectra of the white PHOLED devices. It shows that PHOLEDs made with TAPC HTL possess higher efficiency due to improved triplet exciton confinement in the EML. Additionally, we will discuss to prevent not only loss of triplet excitons but also loss of charge carrier. Therefore, in addition to confinement of triplet excitons, we need to select HTL materials considering to both HTL's highest occupied molecular orbital (HOMO) and the hole drift mobility (μ_h). To illustrate the point, the total thickness of the HTL region in different white OLEDs are kept contact at 700 Å for comparison. Fig. 1 describes the energy band diagrams of three different white PHOLED devices A, B and C. The schematic energy band diagrams of PHOLEDs having three different hole transporting layers of NPB (device A), TCTA (device B) and TAPC (device C) are shown in Fig. 1.

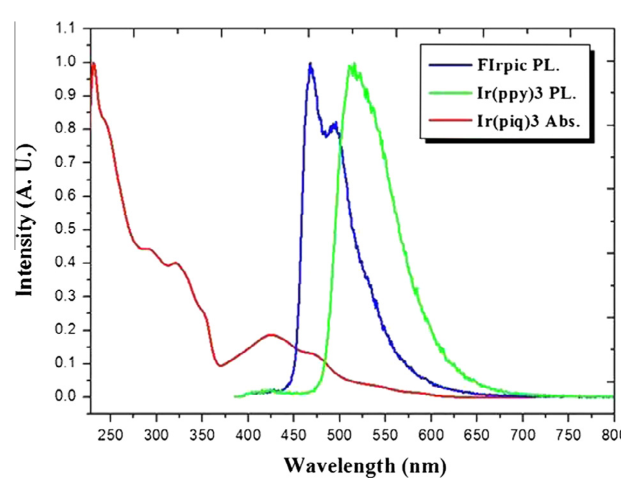

Fig. 2. Phosphorescence spectra measured for FIrpic and Ir(ppy)$_3$ and the absorption spectra of Ir(piq)$_3$.