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Pure-blue fluorescent organic light-emitting diodes by co-doping a supplementary host material into a light-emitting layer as an electron transport ladder

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In this study, an efficient device design strategy in improving the performances of blue fluorescent electroluminescence was demonstrated by co-doping 9-(4-*tert*-butylphenyl)-3,6-bis(triphenylsilyl)-9*H*-carbazole (CzSi) into a light-emitting layer (EML) as an electron transport ladder. 9,10-Bis[4-(6-methylbenzothiazol-2-yl)phenyl]anthracene (DBzA) and 4,4',4''-tris(carbazol-9-yl)triphenylamine (TcTa) were utilized as the emitter and the main host material, respectively. Compared with the device without CzSi, the performances of the co-doped device were improved effectively because of the well-matched energy levels and excellent electron transport ability of CzSi, which facilitated the injection of electrons and thus balanced the distribution of carriers. The feasibility of this device design strategy was demonstrated by investigating single-carrier devices, transient electroluminescent (EL) spectra and normalized EL spectra. Finally, the optimal pure blue fluorescent device realized a maximum brightness, current efficiency, power efficiency and external quantum efficiency (EQE) of up to 28 009 cd m⁻², 7.51 cd A⁻¹, 7.60 lm W⁻¹ and 6.8%, respectively. Even at a high brightness of 1000 cd m⁻², current efficiency and EQE as high as 6.21 cd A⁻¹ and 5.6%, respectively, can still be retained by the same device.

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Introduction

Since the original work on organic light-emitting diodes (OLEDs) by Tang in 1987, numerous endeavors have been devoted to improve the electroluminescent (EL) performances of OLEDs for their potential applications in flat panel displays and solid-state lighting due to their advantages such as self-emitting displays, wide viewing angle, fast response time, high contrast, and so on.^{1–5} Phosphorescent OLEDs have been developed dramatically in terms of red, green and blue OLEDs because of the theoretical 100% internal quantum efficiency (IQE).^{6–8} However, long lifetimes of triplet excited states generally lead to fast triplet-triplet annihilation (TTA) and concentration quenching effects, and thus remarkable efficiency roll-off with increasing current density.^{9–11} Moreover, the high price of heavy metals is the major detracting feature and contributes to the increased cost of phosphorescent OLEDs.¹² Additionally, thermally activated delayed fluorescence (TADF) OLEDs have some weaknesses such as short device lifetimes and poor color

purity even though they can have 100% IQE through reverse intersystem crossing (RISC).¹³ Consequently, the development of efficient fluorescent OLEDs remains a good alternative which has continued to attract interest because of their longer operational lifetimes, higher color purity and broader freedom of molecular design compared with phosphorescent OLEDs, especially in blue OLEDs.¹⁴ For commercial applications, blue light is necessary because it can generate other low-energy emissions, such as green and red emissions, by using a color conversion medium.¹⁵ In addition, blue light is one of the three primary colors in white OLEDs (WOLEDs) which not only transfers energy easily to green and red emitters but also lowers the power consumption.^{16–18} Importantly, combining a blue fluorescent emitter with phosphorescent emitters of other colors has been demonstrated to be efficient in realizing hybrid WOLEDs with high performance.^{19–21}

However, wide energy gaps with low-lying highest occupied molecular orbital (HOMO) levels or high-lying lowest unoccupied molecular orbital (LUMO) levels of most blue emitters result in a high carrier injection barrier.^{22–24} Meanwhile, wide energy gaps of blue emitters compared with red and green emitters make the selection of host materials more difficult. In the past few years, great efforts have been made to optimize the design of devices aiming to further improve the EL performances

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of blue fluorescent OLEDs. For instance, Kim *et al.* developed a highly efficient blue fluorescent OLED with an external quantum efficiency (EQE) of 7.7% and excellent Commission Internationale de l'Éclairage (CIE) coordinates of (0.149, 0.082) by choosing 1,3-bis(carbazol-9-yl)benzene (mCP) as the host material.²⁵ Lu *et al.* obtained a deep-blue fluorescent OLED with a peak EQE of 5.1% and a maximum luminescence of 7800 cd m⁻² by using 4,4',4''-tris(carbazol-9-yl)triphenylamine (TcTa) and 2,6-bis(3-(9H-carbazol-9-yl)phenyl)pyridine (26DCzPPy) as the host materials.²⁶ Previously, we have developed highly efficient blue and green fluorescent OLEDs by employing an electron transport material 9,10-bis[4-(6-methylbenzothiazol-2-yl)phenyl]anthracene (DBzA) and a hole-type material TcTa as the blue emitter and the host material, respectively.^{27,28} These device design strategies were beneficial for broadening the recombination zone, improving carrier trapping and facilitating the balance of holes and electrons.

Encouraged by the excellent EL performances of these devices, in this work, EL performances of DBzA were further improved by co-doping 9-(4-*tert*-butylphenyl)-3,6-bis(triphenylsilyl)-9H-carbazole (CzSi) into a light-emitting layer (EML) as the supplementary host material. In this case, CzSi molecules within the EML acted as electron transport ladders because of their well-matched energy levels and excellent electron transport ability. By adjusting the doping concentration, a co-doped device with higher EL performances especially a lower turn-on voltage ($V_{\text{turn-on}}$) was obtained, attributed to the improved injection of carriers into the EML. Finally, a maximum brightness, current efficiency, power efficiency and EQE of up to 28 009 cd m⁻², 7.51 cd A⁻¹, 7.60 lm W⁻¹ and 6.8%, respectively, were achieved by the co-doped device with 6 wt% CzSi. Even at a high brightness of 1000 cd m⁻², a current efficiency and an external quantum efficiency as high as 6.21 cd A⁻¹ and 5.6%, respectively, can still be retained by the same device.

Experiments

All the organic materials used in this study were obtained commercially and used as received without further purification. Indium-tin-oxide (ITO) coated glass with a sheet resistance of 10 Ω sq⁻¹ was used as the anode substrate. Prior to film deposition, patterned ITO substrates were cleaned with detergent, rinsed in deionized water and finally dried in an oven. All the organic layers were deposited at a rate of 0.1 nm s⁻¹ under high vacuum ($\leq 3.0 \times 10^{-5}$ Pa). The doped and co-doped EMLs were prepared by co-evaporating dopant and host materials from two or three individual sources, and the doping concentrations were modulated by controlling the evaporation rate of the dopant and the supplementary host material. LiF and Al were deposited in another vacuum chamber ($\leq 8.0 \times 10^{-5}$ Pa) with rates of 0.01 and 1.0 nm s⁻¹, respectively, without being exposed to the atmosphere. The thicknesses of these deposited layers and the evaporation rate of individual materials were monitored in a vacuum with quartz crystal monitors. A shadow mask was used to define the cathode and to make

eight emitting dots with an active area of 9 mm² on each substrate. Current density–brightness–voltage (J – B – V) characteristics were measured by using a programmable Keithley source measurement unit (Keithley 2400 and Keithley 2000) with a silicon photodiode. EL spectra were recorded by a C9920-11 Brightness Light Distribution Characteristics Measurement System. Transient EL spectra were recorded by a McScience M6200 Transient EL Measurement System. The EQE of the EL device was calculated based on the photoenergy measured by the photodiode, the EL spectrum, and the current passing through the device.

Results and discussion

The device structure and energy level diagram of the designed OLEDs are depicted in Fig. 1. In this work, DBzA was chosen as the emitter due to its pure blue emission with preferable color stability and well matched energy levels. Herein, the EML was constructed by co-doping DBzA and the supplementary host material CzSi into the predominant host material TcTa. TcTa possesses superior hole transport ability, while CzSi is a traditional electron transport material. Additionally, 1,4,5,8,9,11-hexaazatriphenylene hexacarbonitrile (HAT-CN) was deposited onto the ITO layer as the hole injection layer to improve the injection of holes. A di-[4-(*N,N*-ditolyl-amino)-phenyl]cyclohexane (TAPC) film doped with 0.2 wt% HAT-CN was designed as the hole transport and electron block layer (HTL/EBL) due to its high hole mobility (1×10^{-2} cm² V⁻¹ S⁻¹) and high-lying LUMO energy level (−1.8 eV).²⁹ Meanwhile, 1,3,5-tris(6-(3-(pyridin-3-yl)phenyl)pyridin-2-yl) (Tm3PyP26PyB), which possesses a high electron mobility and a low-lying HOMO energy level (−6.5 eV), was employed as the electron transport and hole block layer (ETL/HBL) material.³⁰ The molecular structures of CzSi, TcTa, DBzA and HAT-CN are also given in Fig. 1.

To optimize the doping concentration of DBzA, a series of devices with the structure of ITO/HAT-CN (6 nm)/HAT-CN (0.2 wt%):TAPC (60 nm)/DBzA (x wt%):TcTa (10 nm)/Tm3PyP26PyB (60 nm)/LiF (1 nm)/Al (100 nm) were firstly manufactured and examined by controlling x to be 12, 14, 16, 18 and 20, respectively.

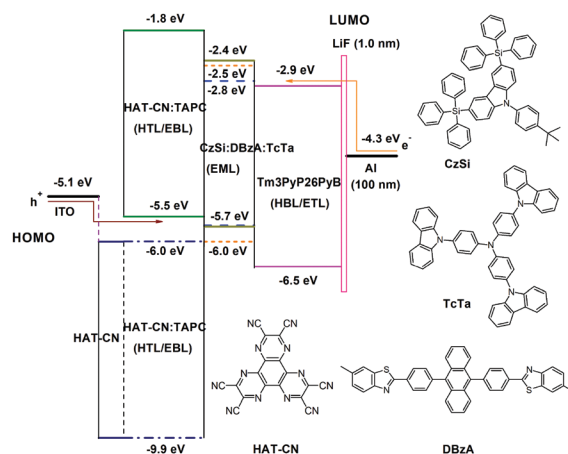


Fig. 1 Proposed energy level diagram of the devices used in this work and the molecular structures of CzSi, TcTa, DBzA and HAT-CN.

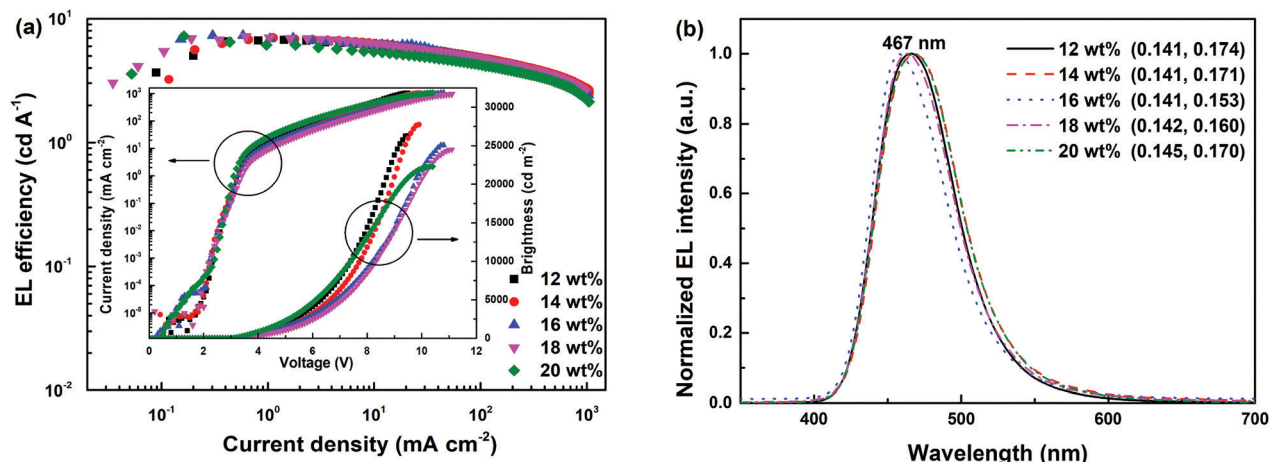


Fig. 2 (a) EL efficiency-current density (η - J) characteristics of devices with different concentrations of DBzA. Inset: Current density-brightness-voltage (J - B - V) characteristics of devices with different concentrations of DBzA. (b) Normalized EL spectra of devices with different concentrations of DBzA operating at 10 mA cm⁻².

The dependence of EL efficiency on the doping concentration of DBzA is depicted in Fig. 2(a), while the J - B - V characteristics of these doped devices are shown in the inset of Fig. 2(a). Experimental results revealed that the 16 wt% device (denoted as device A) gave a maximum current efficiency, power efficiency and EQE of up to 7.33 cd A⁻¹, 7.42 lm W⁻¹ and 6.6% respectively, while the 14 wt% device displayed a maximum brightness of 27 752 cd m⁻² as listed in Table 1. Importantly, the maximum brightness of 27 752 cd m⁻² of the 14 wt% device was nearly three times higher than our previously reported value.²⁷ At a certain brightness of 1000 cd m⁻², current efficiency as high as 6.53 cd A⁻¹ (EQE = 5.9%), which accounted for 89.1% of the maximum current efficiency, was retained by device A. This result means the slow efficiency roll-off of this device. Interestingly, these devices displayed a relatively lower turn-on voltage ($V_{\text{turn-on}}$) compared with our previous report,²⁷ which can be attributed to the fact that the HAT-CN layer is more efficient than the MoO₃ layer in improving hole injection.^{31,32} Normalized EL spectra of these devices operating at a current density of 10 mA cm⁻² were investigated and are shown in Fig. 2(b). All the devices displayed the characteristic emission of the DBzA peak at 467 nm without the emergence of TcTa emission, which implies that most carriers were well trapped by DBzA molecules and recombined within the EML. Correspondingly, device A has the CIE coordinates of (0.141, 0.153). More importantly, there is no obvious difference in emission spectra among

these devices, which proves the excellent color stability of these devices with DBzA as the blue emitter.

To determine the EL mechanisms of these devices with different doping concentrations of DBzA, carriers' distributions on DBzA and TcTa molecules were investigated and analyzed. At relatively low concentrations, as shown in Fig. 3, most holes situated on TcTa molecules because of the identical HOMO levels of TcTa and DBzA which causes a lower hole trapping capacity of DBzA compared with TcTa. However, electrons could be well trapped by DBzA molecules because the LUMO level of DBzA is 0.4 eV lower than that of TcTa and only 0.1 eV higher than that of Tm3PyP26PyB. With an increase in the doping concentration of DBzA, more and more carriers, especially the holes, could be trapped by DBzA molecules. Therefore, an improved balance of carriers as well as broadening of the recombination zone can be obtained. Further increasing the doping concentration to higher than 16 wt%, the EL performances decreased gradually because the balance of carriers was broken. Moreover, high DBzA concentration will cause the aggregation of DBzA molecules, thus increasing the probability of exciton collisions. That is to say, exciton quenching due to high doping concentrations of DBzA may be another reason for the decrease of efficiency.

To achieve effective electron injection and further improve the EL performances of DBzA, a novel device design strategy by

Table 1 The key properties of devices with different doping concentrations of DBzA

Device (wt%)	$V_{\text{turn-on}}$ (V)	L^a (cd m ⁻²)	η_c^b (EQE ^c) (cd A ⁻¹)	η_p^d (lm W ⁻¹)	η_c^e (cd A ⁻¹) (EQE ^f) (1000 cd m ⁻²)	CIE _{xy} ^g
12	2.9	26 827	6.74 (6.1%)	6.61	5.78 (5.2%)	(0.141, 0.169)
14	2.9	27 752	7.02 (6.3%)	6.68	6.07 (5.5%)	(0.141, 0.171)
16	2.8	25 079	7.33 (6.6%)	7.42	6.53 (5.9%)	(0.141, 0.153)
18	2.8	24 508	7.17 (6.5%)	6.82	5.98 (5.4%)	(0.142, 0.160)
20	2.8	22 307	6.48 (5.8%)	6.78	5.06 (4.6%)	(0.145, 0.170)

^a The data for maximum luminance (L). ^b Maximum current efficiency (η_c). ^c Maximum external quantum efficiency (EQE). ^d Maximum power efficiency (η_p). ^e Current efficiency (η_c) at a practical brightness of 1000 cd m⁻². ^f External quantum efficiency (EQE) at a practical brightness of 1000 cd m⁻². ^g Commission Internationale de l'Eclairage coordinates (CIE_{xy}) at 10 mA cm⁻².

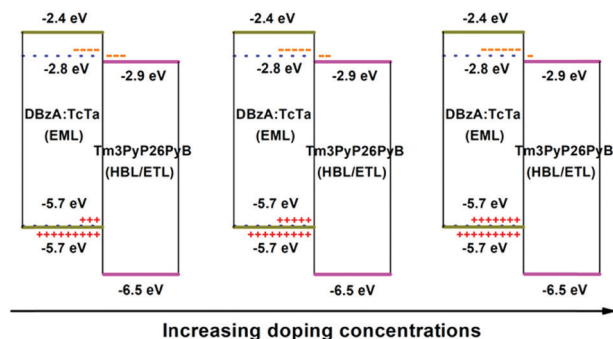


Fig. 3 Schematic representation of carriers' distribution in devices with an increase in the doping concentration of DBzA. The dotted and solid lines within the EML represent the HOMO and LUMO levels of dopants and hosts, respectively. Symbols '–' and '+' represent electrons and holes, respectively.

using CzSi, which possesses excellent electron transport ability and well-matched energy levels, as the supplementary host material was employed. The structure of the designed devices is ITO/HAT-CN (6 nm)/HAT-CN (0.2 wt%):TAPC (60 nm)/CzSi (y wt%):DBzA (16 wt%):TcTa (10 nm)/Tm3PyP26PyB (60 nm)/LiF (1 nm)/Al (100 nm). Initially, the doping concentration of DBzA was determined to be 16 wt% and the doping concentrations of CzSi were adjusted from 2 wt% to 8 wt% with a step of 2 wt%. As shown in Fig. 4(a) and Table 2, the co-doped device with

6 wt% CzSi (denoted as device B) displayed a maximum brightness, current efficiency and EQE of up to 28 009 cd m^{-2} , 7.51 cd A^{-1} , 7.60 lm W^{-1} and 6.8%, respectively. As shown in Fig. 1, the LUMO energy levels of Tm3PyP26PyB, DBzA, CzSi and TcTa molecules are -2.9 eV , -2.8 eV , -2.5 eV and -2.4 eV , respectively. So, CzSi molecules function as electron transport ladders between TcTa and DBzA molecules, thus improving the injection of electrons from the ETL into the EML. Compared with device A, importantly, device B obtained higher EL performances attributed to the well matched LUMO energy levels and excellent electron transport ability of CzSi. In this case, the co-doped CzSi molecules within the EML functioned as electron transport ladders, thus facilitating the injection of electrons into the EML. As a result, improved carrier balance and broadening of the recombination zone were realized in these co-doped devices. As shown in Fig. 4(b), the emission of DBzA peaked at 469 nm, and no marked TcTa and CzSi emissions were observed. Additionally, the red shift of the DBzA emission peak was only 2 nm, which has no significant influence on color purity. These experimental results demonstrated that co-doping CzSi into the hole dominant EML as the electron transport ladder is an effective device design strategy to improve the EL performances of the blue fluorescent emitter DBzA without sacrificing the color purity.

To further optimize the doping concentration of DBzA in co-doped devices, based on device B, two devices were fabricated

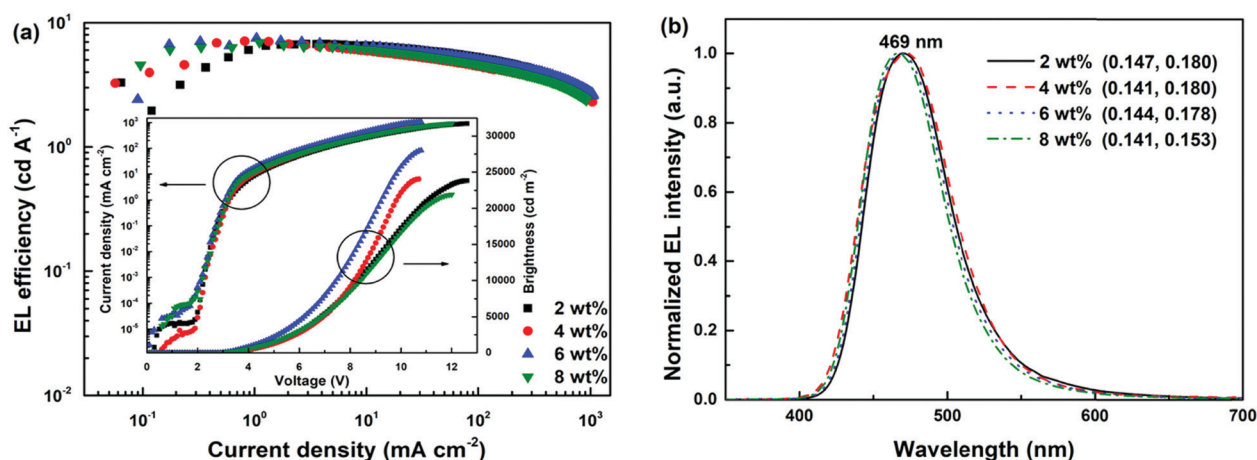


Fig. 4 (a) EL efficiency–current density (η – J) characteristics of DBzA co-doped devices with different co-doping concentrations of the supplementary host CzSi. Inset: Current density–brightness–voltage (J – B – V) characteristics of devices with different concentrations of CzSi. (b) Normalized EL spectra of DBzA co-doped devices with different co-doping concentrations of the supplementary host CzSi operating at 10 mA cm^{-2} .

Table 2 The key properties of DBzA co-doped devices with different doping concentrations of the supplementary host CzSi

Device (wt%)	$V_{\text{turn-on}}$ (V)	L^a (cd m^{-2})	η_c^b (EQE ^{c}) (cd A^{-1})	η_p^d (lm W^{-1})	η_c^e (cd A^{-1}) (EQE ^{f}) (1000 cd m^{-2})	CIE $_{xy}^g$
2	2.7	23 837	6.75 (6.1%)	6.19	6.34 (5.7%)	(0.147, 0.180)
4	2.5	24 028	7.10 (6.4%)	6.97	5.56 (5.0%)	(0.141, 0.180)
6	2.7	28 009	7.51 (6.8%)	7.60	6.21 (5.6%)	(0.144, 0.178)
8	2.8	21 912	6.93 (6.2%)	6.80	5.72 (6.1%)	(0.141, 0.153)

^{a} The data for maximum luminance (L). ^{b} Maximum current efficiency (η_c). ^{c} Maximum external quantum efficiency (EQE). ^{d} Maximum power efficiency (η_p). ^{e} Current efficiency (η_c) at a practical brightness of 1000 cd m^{-2} . ^{f} External quantum efficiency (EQE) at a practical brightness of 1000 cd m^{-2} . ^{g} Commission Internationale de l'Eclairage coordinates (CIE $_{xy}$) at 10 mA cm^{-2} .

Table 3 The key properties of DBzA co-doped devices with different doping concentrations of DBzA

Device (wt%)	$V_{\text{turn-on}}$ (V)	L^a (cd m $^{-2}$)	η_c^b (EQE ^{c}) (cd A $^{-1}$)	η_p^d (lm W $^{-1}$)	η_c^e (cd A $^{-1}$) (EQE ^{f}) (1000 cd m $^{-2}$)	CIE $_{xy}^g$
14	2.8	23 442	7.18 (6.5%)	7.27	5.47 (4.9%)	(0.140, 0.149)
16	2.7	28 009	7.51 (6.8%)	7.60	6.21 (5.6%)	(0.144, 0.178)
18	2.6	23 302	7.23 (6.5%)	7.10	6.26 (5.6%)	(0.143, 0.169)

^a The data for maximum luminance (L). ^b Maximum current efficiency (η_c). ^c Maximum external quantum efficiency (EQE). ^d Maximum power efficiency (η_p). ^e Current efficiency (η_c) at a practical brightness of 1000 cd m $^{-2}$. ^f External quantum efficiency (EQE) at a practical brightness of 1000 cd m $^{-2}$. ^g Commission Internationale de l'Eclairage coordinates (CIE $_{xy}$) at 10 mA m $^{-2}$.

by adjusting the doping concentration of DBzA to be 14 wt% and 18 wt%, respectively. As listed in Table 3, EL performances of both devices were lower than that of device B. So 16 wt% was also the optimal doping concentration of DBzA for these co-doped devices, which further proves the best balance of carriers in the 16 wt% DBzA doped device. In addition, this work also verified that CzSi is a proper electron transport ladder in improving the EL performances of DBzA.

To investigate the influence of the thicknesses of TAPC and Tm3PyP26PyB layers on the device performances in this strategy, two devices with the structures of ITO/HAT-CN (6 nm)/HAT-CN (0.2 wt%):TAPC (50 nm)/CzSi (6 wt%):DBzA (16 wt%):TcTa (10 nm)/Tm3PyP26PyB (60 nm)/LiF (1 nm)/Al (100 nm) (denoted as device C) and ITO/HAT-CN (6 nm)/HAT-CN (0.2 wt%):TAPC (50 nm)/CzSi (6 wt%):DBzA (16 wt%):TcTa (10 nm)/Tm3PyP26PyB (70 nm)/LiF (1 nm)/Al (100 nm) (denoted as device D), respectively, were fabricated and compared with device B. As shown in Table 4 and Fig. 5(a), device B obtained the highest EL performances and displayed the slowest efficiency roll-off at

the same time. Consequently, current efficiencies at a certain brightness of 1000 cd m $^{-2}$ of devices B, C, and D accounted for 82.7%, 78.2% and 77.5% of the maximum current efficiencies, respectively. These results can be interpreted as the improved balance of holes and electrons and the broadening of the recombination zone in device B. Fig. 5(b) gave the normalized EL spectra of device B operating at different current densities. With increasing current density, only DBzA characteristic emission was observed, and thus no distinguishable discrepancy of EL spectra was found, which further demonstrates the superior color stability of these devices.

To compare the current density characteristics of the films with or without the co-doping of CzSi, two hole only devices (HODs) and two electron only devices (EODs) were fabricated and investigated with the structures as follows:

HOD 1: ITO/HAT-CN (6 nm)/HAT-CN (0.2 wt%):TAPC (20 nm)/DBzA (16 wt%):TcTa (60 nm)/HAT-CN (0.2 wt%):TAPC (20 nm)/Al (100 nm),

Table 4 The key properties of DBzA co-doped devices with TAPC and Tm3pyP26PyB layers of different thicknesses

Device	$V_{\text{turn-on}}$ (V)	L^a (cd m $^{-2}$)	η_c^b (EQE ^{c}) (cd A $^{-1}$)	η_p^d (lm W $^{-1}$)	η_c^e (cd/A) (EQE ^{f}) (1000 cd m $^{-2}$)	CIE $_{xy}^g$
B	2.7	28 009	7.51 (6.8%)	7.60	6.21 (5.6%)	(0.144, 0.178)
C	2.7	24 067	6.94 (6.3%)	6.74	5.43 (4.9%)	(0.144, 0.134)
D	2.9	21 807	7.39 (6.7%)	7.08	5.73 (5.2%)	(0.142, 0.168)

^a The data for maximum luminance (L). ^b Maximum current efficiency (η_c). ^c Maximum external quantum efficiency (EQE). ^d Maximum power efficiency (η_p). ^e Current efficiency (η_c) at a practical brightness of 1000 cd m $^{-2}$. ^f External quantum efficiency (EQE) at a practical brightness of 1000 cd m $^{-2}$. ^g Commission Internationale de l'Eclairage coordinates (CIE $_{xy}$) at 10 mA cm $^{-2}$.

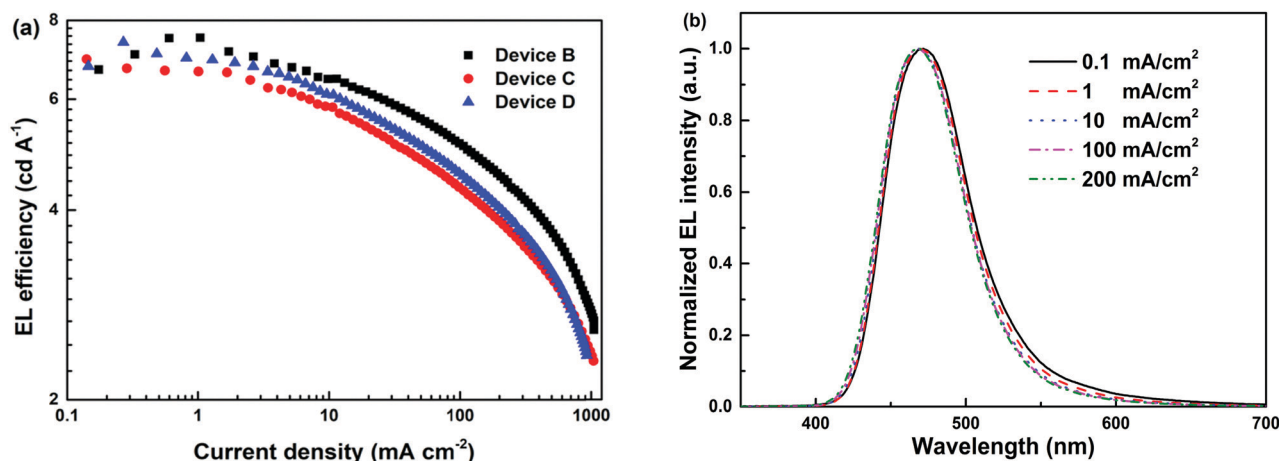


Fig. 5 (a) EL efficiency–current density (η – J) characteristics of devices B, C and D. (b) Normalized EL spectra of device B operating at different current densities.

HOD 2: ITO/HAT-CN (6 nm)/HAT-CN (0.2 wt%):TAPC (20 nm)/CzSi (6 wt%):DBzA (16 wt%):TcTa (60 nm)/HAT-CN (0.2 wt%):TAPC (20 nm)/LiF (1 nm)/Al (100 nm),

EOD 1: ITO/Tm3PyP26PyB (20 nm)/DBzA (16 wt%):TcTa (60 nm)/Tm3PyP26PyB (20 nm)/LiF (1 nm)/Al (100 nm),

EOD 2: ITO/Tm3PyP26PyB (20 nm)/CzSi (6 wt%):DBzA (16 wt%):TcTa (60 nm)/Tm3PyP26PyB (20 nm)/LiF (1 nm)/Al (100 nm).

Current density–voltage (J – V) characteristics of HODs and EODs are shown in Fig. 6. At a certain current density, the driving voltage of HOD 2 is higher than that of HOD 1. This result confirmed that hole transport was delayed by CzSi molecules because the HOMO level of CzSi is 0.3 eV lower than that of DBzA. Simultaneously, electron transport in EOD 2 is slightly slower compared with that in EOD 1. These phenomena can be attributed to the presence of CzSi molecules within the EML, which increases the average distance between DBzA molecules, and thus delayed the electron hopping between DBzA molecules. Therefore, the co-doping of CzSi molecules helps to broaden the recombination zone of holes and electrons within the EML. To verify the efficacy of the device design strategy, as shown in Fig. 7, the transient EL spectra of devices A and B were also investigated. At 0.1, 1, 10, 100 and 200 mA cm^{−2}, the exciton lifetimes of device A were 140, 320, 380, 180 and 180 ns, respectively, while the exciton lifetimes of device B were 340, 800, 500, 240 and 240 ns, respectively. In this case, the longer exciton lifetimes of device B compared with device A further demonstrated the fact that the presence of CzSi molecules within the EML helps to decrease the density of excitons, thus reducing the exciton quenching probability.

To better understand the improvement mechanisms of EL performances in device B, two other devices with the structures of ITO/HAT-CN (6 nm)/HAT-CN (0.2 wt%):TAPC (60 nm)/DBzA (16 wt%):TcTa (10 nm)/Ir(mppy)₃ (2 wt%):Tm3PyP26PyB (2 nm)/Tm3PyP26PyB (60 nm)/LiF (1 nm)/Al (100 nm) (denoted as device E) and ITO/HAT-CN (6 nm)/HAT-CN (0.2 wt%):TAPC (60 nm)/CzSi (6 wt%):DBzA (16 wt%):TcTa (10 nm)/Ir(mppy)₃ (2 wt%):Tm3PyP26PyB (2 nm)/Tm3PyP26PyB (60 nm)/LiF

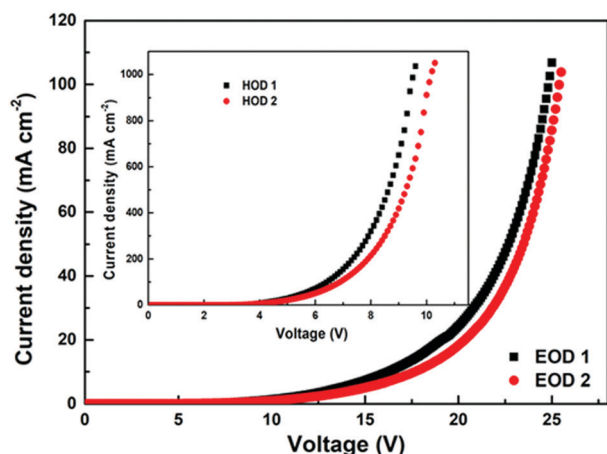


Fig. 6 Current density–voltage (J – V) characteristics of hole-only and electron-only devices.

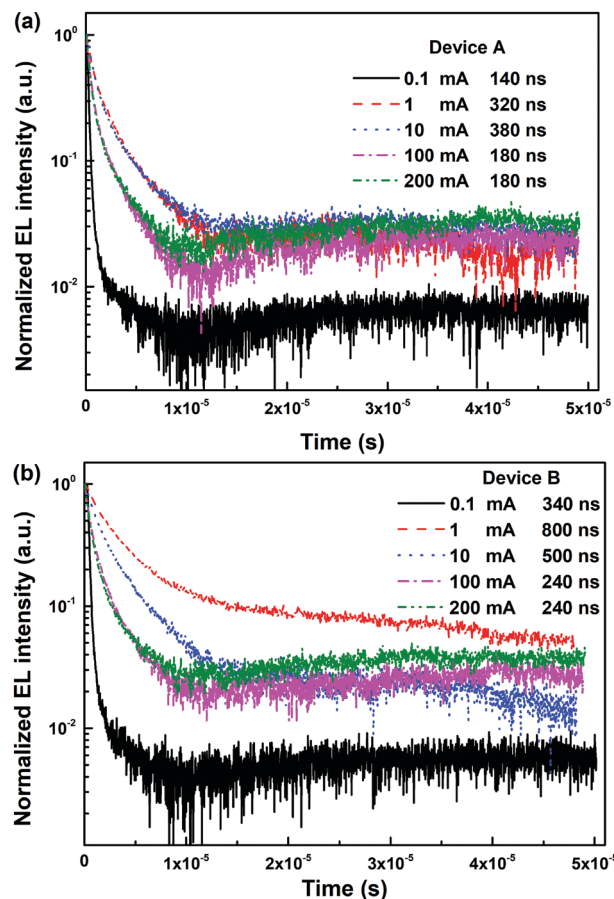


Fig. 7 Normalized EL transient spectra of devices A (a) and B (b) operating at different current densities.

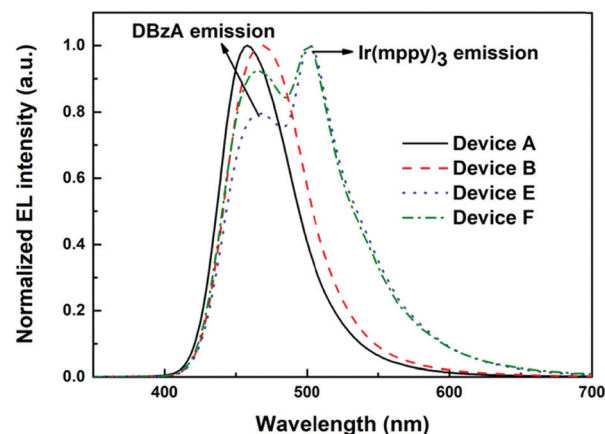


Fig. 8 Normalized EL spectra of devices A, B, E and F operating at 10 mA cm^{−2}.

(1 nm)/Al (100 nm) (denoted as device F) were designed and manufactured specially. Here, the 2 nm 2 wt% Ir(mppy)₃ doped Tm3PyP26PyB film was designed as a sensitized layer to probe the shift of the recombination zone. The EL spectra of devices A, B, E and F operating at 10 mA cm^{−2} were recorded and are depicted in Fig. 8. Except for the DBzA emission, relatively

stronger Ir(mppy)₃ emissions can be observed in devices E and F, which imply that some carriers can be trapped by Ir(mppy)₃ molecules and cause the formation of excitons on Ir(mppy)₃ molecules. Obviously, the emission intensity of DBzA in device F is stronger than that in device E. This result indicates the shift of the recombination zone toward the anode, thus broadening the recombination zone.

Conclusions

In summary, an efficient blue fluorescent OLED with the electron transport material DBzA as the emitter was developed by using the supplementary host CzSi as the electron transport ladder. By optimizing the doping concentration of CzSi, a maximum brightness, current efficiency, power efficiency and EQE of up to 28 009 cd m⁻², 7.51 cd A⁻¹, 7.60 lm W⁻¹ and 6.8%, respectively, were realized. Experimental results revealed that the co-doping of CzSi molecules not only improved the injection of electrons into the EML but also delayed the transport of holes within the EML, thus facilitating the balance of carriers and broadening the recombination zone. Consequently, the recombination probability of holes and electrons was enhanced and the quenching of excitons was suppressed. Our investigations demonstrated the efficacy of using CzSi as the electron transport ladder and provided a new perspective in realizing highly efficient blue fluorescent OLEDs.

Conflicts of interest

There are no conflicts to declare.

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