



# Improved power efficiency of blue fluorescent organic light-emitting diode with intermixed host structure

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## ABSTRACT

High power efficiency (PE) p-bis(p-N,N-diphenyl-aminostyryl)benzene (DSA-ph) based fluorescent blue organic light-emitting diode (OLED) is demonstrated by utilizing intermixed host (IH) structure. The PE outperforms those devices based on single host (SH), mixed host (MH), and double emitting layers (DELs). By further optimizing the intermixed layer, peak PE of the IH device is increased up to 8.7 lm/W (1.7 times higher than conventional SH device), which is the highest value among the DSA-ph based blue device reported so far.

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## 1. Introduction

Organic light-emitting diodes (OLEDs) have attracted considerable interest owing to their potential application in flat-panel displays and lighting technology. Blue OLED (BOLED) is a key fundamental unit for full-color display as well as solid-state lighting. However, a number of technological challenges still need to be resolved for BOLED: e.g. increasing device efficiency, lowering driving voltage, and improving the operational stability. Despite phosphorescent BOLED can obtain a high internal quantum efficiency, it is difficult to achieve a stable phosphorescent emission over the entire operational lifetime of the device. Fluorescent BOLED has the advantage over phosphorescent device in terms of device stability. However, most of the blue fluorescent materials exhibit much lower efficiency compared to phosphorescent materials. Therefore, the selection of suitable device structure for different fluorescent emitters to obtain high efficiency BOLEDs are indispensable.

In 2004, Chen group [1] reported an efficient and stable blue fluorescent OLED based on p-bis(p-N,N-diphenyl-aminostyryl)benzene (DSA-ph), which shows superior efficiency over other common fluorescent emitters, such as 4,4-bis(2,2-diphenyl-ethen-1-yl)-biphenyl (DPVBi), 4,4'-bis(9-ethyl-3-carbazovinylen)-1,

1'-biphenyl (BCzVBi), etc. Up to now, several works have been done to improve the efficiency of the DSA-ph based BOLED, and the device performances have been greatly improved [2]. From the device architecture point of view, mixed host (MH) and double emitting layers (DELs) structures are reported as an effective method to obtain high performance monochromatic OLED compared to single host (SH) structure because of the reduction in charge accumulation and extension of the emission zone [3–5]. Additionally, in 2009, Jang and Shin proposed an intermixed host (IH) structure, which was proved to be a feasible method to improve the performance of green phosphorescent OLEDs [6].

In this letter, we first introduce the IH structure into DSA-ph based BOLED and fabricate a series of devices with different structures as mentioned above. The device with IH structure shows the highest power efficiency (PE) compared to other devices. A further investigation is also carried out to elucidate the role of intermixed layer. Significantly, a high PE of 8.7 lm/W and low turn-on voltage (~2.7 V) are achieved in the optimized device. The obtained PE is the highest value among the DSA-ph based BOLED reported so far [1,7–10].

## 2. Experiment

Devices were fabricated on glass substrates precoated with indium tin oxide (ITO) anode with a sheet resistance of ~20 Ω/□. N,N'-bis(naphthalene-1-yl)-N,N'-bis(phenyl)-benzidine

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(NPB) serves as a hole transport layer (HTL) and hole transport host, 2-methyl-9,10-di(2-naphthyl) anthracene (MADN) is used as an electron transport host, DSA-ph is used as blue fluorescent dopant, 4,7-diphenyl-1,10-phenanthroline (BPhen) acts as an electron transport layer (ETL), finally, 1 nm LiF covered by 100 nm Al is used as cathode. Fig. 1 illustrated the schematic diagrams of the devices and simplified energy-levels diagram of materials used in this work. In MH and IH devices, the mixture ratio of NPB and MADN is 1:1 (NPB<sub>0.5</sub>MADN<sub>0.5</sub>). The doping ratio of DSA-ph for all the devices is 5 wt%.

All the organic layers were thermally deposited under high vacuum ( $< 10^{-6}$  Torr) at a rate of 1–2 Å/s monitored in situ with the quartz oscillator. After the deposition of LiF, the samples were transferred to metal chamber suffering from a vacuum break, the metal cathode was then vapor deposited onto the organic films. The current–voltage–luminance characteristics were measured by a PR650 spectrascan spectrometer combined with a Keithley 2400 programmable voltage–current source. All measures were carried out at room temperature under ambient conditions.

### 3. Results and discussion

The current efficiency–luminance–power efficiency (CE–L–PE) curves are plotted in Fig. 2. We can clearly see that, when the ratio of NPB/MAN is 1:1, the MH device exhibits quite low efficiency, which is even inferior to the SH device, while the IH device obtains the highest efficiency among these devices. We attribute the low efficiency in the MH structure to the current leakage [11] caused by the presence of NPB molecular in the emission layer (EML). As demonstrated in Fig. 3, the MH shows the maximum current density at the same applied voltage. This may be because the NPB in the MH can form an additional transport channel for carriers from the EML to HTL/ETL, which will increase the current leakage towards the electrode [12,13]. Thus, fewer excitons can be confined in the EMLs and thereby worsens the emission efficiency. This is further proved by the hole-only and electron-only devices. As shown in Fig. 4, both the electron current and hole current are obviously increased in the MH device compared to SH device. Higher efficiency in the DELs device compared with the SH device is because the introduction of double EMLs can effectively broaden the exciton recombination zone [14–16]. However, relative severe exciton quenching will still exist between these two EMLs due to the inherent carrier accumulation at the heterojunction. Whereas the IH device, which can be regarded as the integration of the MH and DELs devices, could not only take advantage of the “current leakage” characteristic of MH structure to reduce the carrier accumulation at the DELs heterojunction and subsequently lessen

the exciton quenching [17,18], but also further broaden exciton distribution area relative to the DELs device. Thus, the IH device achieves the highest efficiency. Furthermore, reduction of the sharp heterojunction interface between NPB and MADN in the IH device could also facilitate carrier transport and subsequently reduce the turn-on voltage, thereby leading to a high peak PE of

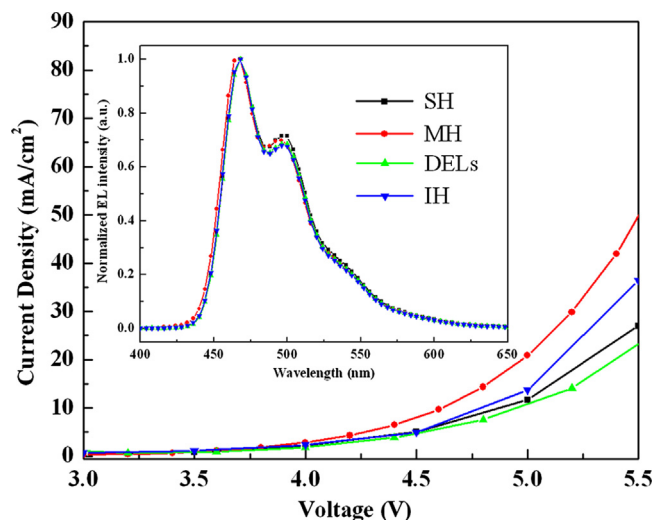


Fig. 2. Plots of CE–L–PE characteristics of the devices.

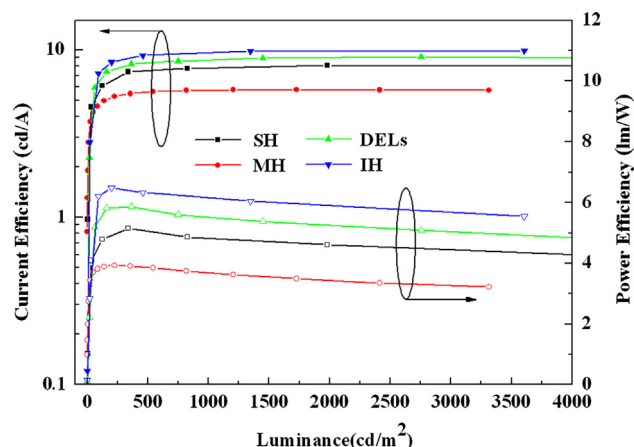


Fig. 3. Current density–voltage (J–V) characteristics of the four devices. The inset is their normalized EL spectra at 5.0 V. The little blue shift trend from SH to MH case results from the optical interference effect due to the different positions of recombination zone.

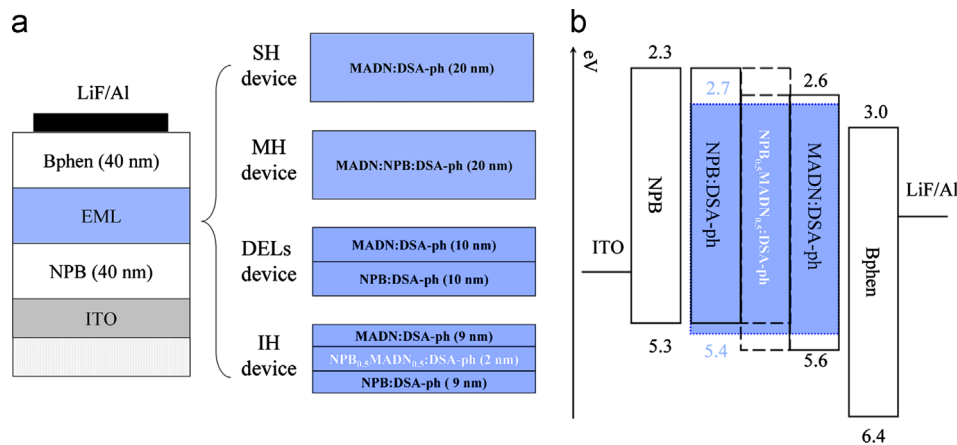


Fig. 1. (a) Schematic diagrams of fabricated devices and (b) simplified energy-level diagram of materials in the devices.

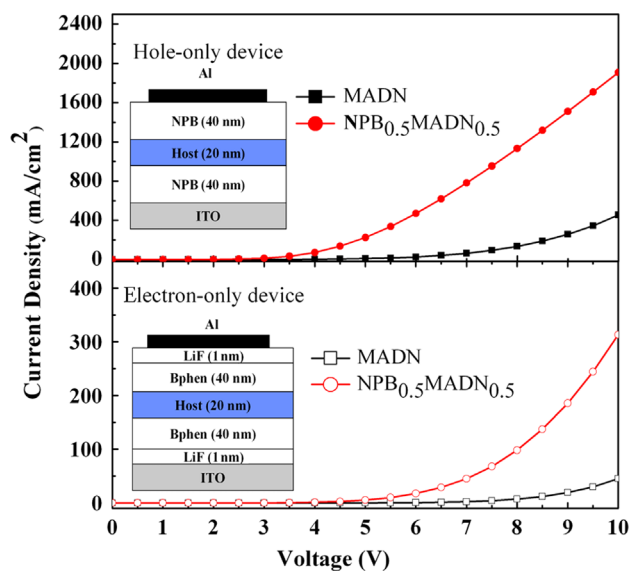


Fig. 4. The  $J$ - $V$  curves of hole only and electron only devices.

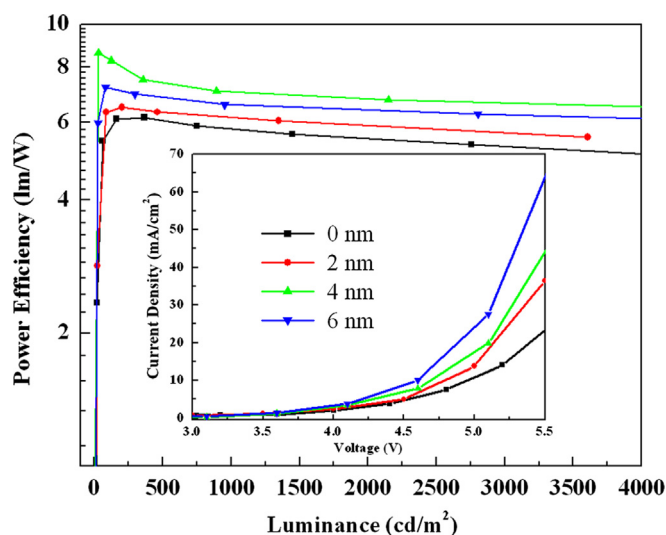


Fig. 5. PE-L characteristics of four IH devices with different intermixed layer thicknesses. The inset is the  $J$ - $V$  characteristics of the four devices.

6.5 lm/W at 200 cd/m<sup>2</sup>, which is almost 1.25 times higher than the peak PE of the SH device.

To further elucidate the role of intermixed layer, another two sets of devices were fabricated and investigated. Here, the thickness of intermixed layer in the IH device was increased to 4 nm and 6 nm, respectively. The maximum PE reached as high as 8.6 lm/W when the interlayer thickens to 4 nm (Fig. 5), indicating that the exciton distribution area can be effectively broadened by tuning the interlayer thickness. However, the device efficiency begins to drop as the interlayer thickness increases to 6 nm, which can be attributed to the higher current leakage in the device (as the  $J$ - $V$  curves shown in Fig. 5 inset).

In succession, we fixed the thickness of intermixed layer at 4 nm, and varied the doping ratio of NPB/MADN in the interlayer to be 2:1, 1:1, 1:2 (NPB<sub>2</sub>MADN<sub>1</sub>, NPB<sub>0.5</sub>MADN<sub>0.5</sub>, and NPB<sub>1</sub>MADN<sub>2</sub> to present), respectively. The PE and CE characteristics of these devices are shown in Fig. 6. We can notice that a peak PE of 8.7 lm/W is obtained in device with NPB<sub>2</sub>MADN<sub>1</sub> which is nearly 1.7 times than SH device, while a reduced efficiency roll-off is observed in the device with NPB<sub>1</sub>MADN<sub>2</sub>. This is because the lower exciton and

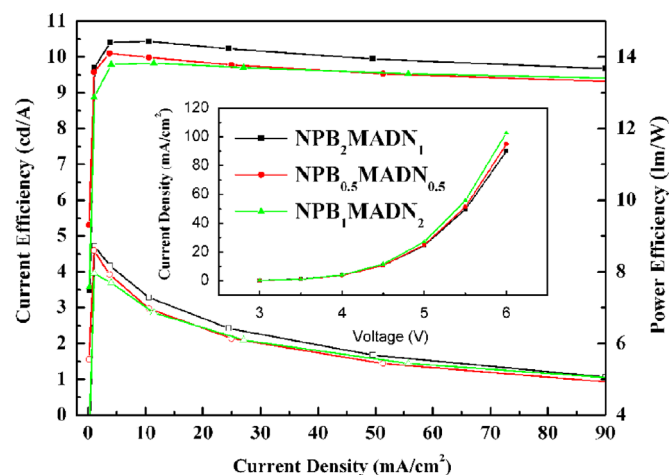


Fig. 6. CE- $J$ -PE characteristics of three devices with various NPB/MADN doping ratio in intermixed layer. The inset is the  $J$ - $V$  characteristics of the devices.

Table 1

The EL characteristics of some of the high performance DSA-ph based OLEDs.

Device	Turn-on voltage (V)	Voltage at 1000 cd/m <sup>2</sup> (V)	Max. PE (lm/W)	CIE coordinates (x, y)
E1 <sup>a</sup>	–	–	5.5	(0.16, 0.32)
E2 <sup>b</sup>	–	–	4.8	(0.16, 0.35)
E3 <sup>c</sup>	4	7	4.5	(0.15, 0.34)
E4 <sup>d</sup>	2.8	5.2	5.0	(–)
E5 <sup>e</sup>	–	–	7.9	(0.15, 0.29)
This work	2.7	4.5	8.7	(0.15, 0.29)

<sup>a</sup> Device E1: ITO/CF<sub>x</sub>/NPB (70 nm)/MADN:DSA-ph (3 wt%) (40 nm)/Alq<sub>3</sub> (10 nm)/LiF (1 nm)/Al (200 nm) [1]

<sup>b</sup> Device E2: ITO/CF<sub>x</sub>/NPB (70 nm)/DPVPA:DSA-ph (3 wt%) (40 nm)/Alq<sub>3</sub> (10 nm)/LiF (1 nm)/Al (200 nm) [2]

<sup>c</sup> Device E3: ITO/m-MTDATA:F4-TCNQ (3 wt%) (30 nm)/NPB (10 nm)/NPB:DSA-ph (3 wt%) (20 nm)/MADN:DSA-ph (3 wt%) (30 nm)/TPBi (15 nm)/LiF (1 nm)/Al (100 nm) [5]

<sup>d</sup> Device E4: ITO/NPB (40 nm)/MADN:DSA-ph (3 wt%)/MADN<sub>0.5</sub>NPB<sub>0.5</sub>:DSA-ph (30 nm)/Bphen (30 nm)/LiF (1 nm)/Al [6]

<sup>e</sup> Device E5: ITO/CF<sub>x</sub>/NPB:CuPc (50%) (40 nm)/NPB (30 nm)/MADN:DSA-ph (40 nm)/Alq<sub>3</sub> (10 nm)/LiF (1 nm)/Al (200 nm) [7]

charge confinement (as deduced from  $J$ - $V$  curves in Fig. 6 inset) in the device with NPB<sub>1</sub>MADN<sub>2</sub> with respect to other two devices will reduce the singlet-singlet exciton quenching and singlet-triplet exciton quenching behaviors especially at higher current density [19–21].

Table 1 summarized the performances of DSA-ph based BOLEDs. Our devices achieve a maximum power efficiency of 8.7 lm/W, which, to the best of our knowledge, is the best result among the DSA-ph based BOLEDs reported so far. It should be noted that the device efficiency studied in this work is only measured in the forward direction without the use of an integrating sphere or outcoupling. When the devices are measured with an integrating sphere, all photons should be taken into account. In this case, to get the total efficiency, a factor of 1.7–2.3 should be applied to the forward-viewing efficiencies [22,23]. Moreover, according to previous reports [24,25], longer operational lifetime can also be expected due to the blur of the interface heterojunction and reduction of the driving voltage.

#### 4. Conclusion

In summary, a record high PE is obtained in the DSA-ph based fluorescent BOLED utilizing the IH structure, which can efficiently

facilitate the carrier transport as well as regulate exciton distribution within the EML. The efficiency of the present device can still be drastically improved by adopting p–i–n structure to achieve more balanced carrier injection and using a periodic outcoupling structure to increase the light extraction. It is anticipated that the IH structure can be applicable to other blue fluorescent materials and this work might be a significant reference for further research towards high PE BOLEDs. We hope more efficient BOLEDs can be realized based on the IH structure in the future.

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