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# High-performance non-doped pure-blue electroluminescent device based on bisphenanthroimidazole derivative with twisted donor-acceptor structure

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#### ABSTRACT

The development of efficient pure-blue emitters is of great significance for achieving high-quality display and lighting. Herein, a pure-blue emitter TPA-DPPI comprised of bisphenanthroimidazole and triphenylamine units with bipolar carrier transport property is designed and synthesized. For the two phenanthroimidazole units, one acts as the electron acceptor moiety, and the other is introduced to twist the molecule in order to suppress the intermolecular interactions in neat film. Highly twisted molecular configuration endows the compound with a high photoluminescence quantum efficiency yield of 0.56 in neat film. The non-doped device using TPA-DPPI as an emissive layer shows a pure-blue emission with a Commission International de l'Eclairage coordinates of (0.146, 0.097) and a high external quantum efficiency of 5.20%.

#### 1. Introduction

In the past few decades, organic light-emitting diodes (OLEDs) have been paid considerable attention owing to their potential applications in flat-panel displays and solid-state lighting sources [1]. High-performance pure-blue emitters meeting Commission International de l'Eclairage (CIE) coordinates (0.14, 0.08) defined by the National Television System Committee (NTSC) are of particular significance for full-color displays and white lighting [2,3]. Phosphorescent materials based on organic-metal complexes can utilize both the singlet and triplet excitons via heavy atoms induced spin-orbit coupling and achieve 100% internal quantum efficiency (IQE) theoretically [4-6]. However, efficient pure-blue phosphors with CIE coordinates around (0.14, 0.08) are extremely rare due to the inherent difficulty in molecular design. Furthermore, high cost of phosphorecent materials is also disadvantageous for the large-scale practical applications. Thermally activated delayed fluorescence (TADF) materials proposed recently can also achieve 100% exciton utilization efficiency (EUE) by efficient reverse intersystem crossing (RISC), but the significant intramolecular charge transfer properties of TADF materials usually contribute to red-shifted emission spectra, which increases the difficulty of designing pure-blue TADF materials [7-10]. Moreover, the severe

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The electroluminescence (EL) performance of blue emitting materials is often inferior to that of green and red emitters because of their intrinsically wide band gaps which result in poor charge injection and transportation in the emitting layer [11,12]. The choice of hosts of blue materials is also a nerve-wracking issue, because the host materials must possess even larger band gaps and well-matched frontier molecular orbital energy levels. Construction of non-doped devices is an efficient strategy to solve the above-mentioned issues. On the one hand, the configuration of blue materials must be highly twisted for avoiding aggregation induced quenching and red shifting of emission. On the other hand, the blue materials must be bipolar for enlarging the exciton recombination region and suppressing the efficiency roll-off at high current density.

In this contribution, we designed and synthesized a twisted donoracceptor (D-A) type blue emitting molecule, *N*,*N*-diphenyl-4'-(1-(4-(2phenyl-1*H*- phenanthro[9,10-*d*]imidazole-1-yl)phenyl)-1*H*-phenanthro [9,10-*d*]imidazole-2-yl)-[1,1'-biphenyl]-4-amine, namely TPA-DPPI. In







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this molecule, triphenylamine (TPA) is used as the electron donor moiety, and the adjacent PPI is chosen as the electron acceptor unit. Additional PPI group is introduced to twist the molecule in order to suppress the intermolecular interactions in neat film, which can not only improve photoluminescence quantum efficiency yield (PLQY), but also can lead to blue-shift of the fluorescent emission in neat film. As a result, the compound exhibits a high PLQY of 0.56 in neat film and blue emission with a peak wavelength at 460 nm. In addition, TPA-DPPI also exhibits bipolar carrier transporting characteristic from the results of the hole-only and electron-only devices. The non-doped OLED using TPA-DPPI as the emitting layer shows pure-blue emission with a CIE coordinates (0.146, 0.097) and high device performance with a maximum external quantum efficiency (EQE) of 5.20%, which is among the highest values reported for non-doped pure-blue OLEDs [13–18].

### 2. Results and discussion

The synthetic procedures and molecular structure of TPA-DPPI were presented in Scheme 1. The intermediate NO<sub>2</sub>-PPI was prepared from phenanthrene-9,10-dione, benzaldehyde, 4-nitroaniline and ammonium acetate. The key precursor NH<sub>2</sub>-PPI was synthesized through reducing NO<sub>2</sub>-PPI using Pd/C and hydrazine hydrate. The final product was synthesized through a one-pot cyclizing reaction by refluxing a mixture of phenanthrene-9,10-dione, NH<sub>2</sub>-PPI, TPAPh-CHO and ammonium acetate in acetic acid for 5 h [19–21]. TPA-DPPI and the intermediates were further characterized by <sup>1</sup>H nuclear magnetic resonance (NMR) (Fig. S1~Fig. S3), mass spectrometry (Fig. S4~Fig. S6) and elemental analysis. <sup>13</sup>C NMR spectrum of TPA-DPPI was not available owing to the poor solubleness.

The thermal properties of TPA-DPPI were investigated using thermal gravimetric analysis (TGA) and differential scanning calorimetric (DSC) measurements (Fig. S7), the corresponding thermal data are summarized in Table S1. The compound exhibited excellent thermal stability with a thermal decomposition temperature ( $T_d$ , corresponding to 5% weight loss) of 535 °C. A high melting point of 355 °C and a high glass-transition temperature ( $T_g$ ) of 212 °C were also obtained, which were high enough for application in OLEDs and should be attributed to the high molecular weight and rigid skeleton of DPPI. The excellent thermal property of TPA-DPPI is advantageous to form stable thin films upon thermal evaporation, and thus improves the operational performance of the OLEDs.

The electrochemical property of TPA-DPPI was measured by cyclic voltammetry (CV). As depicted in Fig. S8, TPA-DPPI showed an

oxidation process with the onset voltage of *ca.* 0.47 V. Therefore, the estimated highest occupied molecular orbital (HOMO) level is -5.27 eV for TPA-DPPI with regard to the energy level of ferrocene (4.8 eV below vacuum). No clear reduction wave was observed within the potential window of the CV, the lowest unoccupied molecular orbital (LUMO) level was deduced from the HOMO energy level and the optical band gap (3.05 eV) determined by the onset of the absorption spectrum (Fig. 2a). The LUMO level was calculated to be -2.22 eV for TPA-DPPI.

To gain insight into the structure-property relationship of TPA-DPPI at molecular level, density functional theory (DFT) calculations with a B3LYP/6-31G (d,p) basis set were carried out using Gaussian 09 package. The optimized structure and electron density distribution of the compound are shown in Fig. 1. Large dihedral angles of 88.93° and 68.10° could be observed between each of the two PI moieties and the C<sub>6</sub>H<sub>4</sub> linker (P1) between them, respectively. In addition, the dihedral angles were 29.39° and 33.63° between the C<sub>6</sub>H<sub>4</sub> linker (P2) and adjacent imidazole/TPA units. The highly twisted molecular conformation can effectively suppress intermolecular  $\pi$ - $\pi$  interactions, leading to a high PLOY in neat film. According to DFT calculations, the HOMO of TPA-DPPI was predominantly located on the TPA moiety, P2 linker and partly on the imidazole ring. The LUMO was mainly distributed on P2 and the adjacent PPI unit. It is worth noting that the LUMO and HOMO orbits showed a slight overlap on the imidazole ring and P2, which could contribute to highly efficient fluorescence radiative decay. In addition, the additional PPI unit scarcely participated in the FMO distributions but played a role in twisting the molecule. Theoretical calculation by time-dependent DFT (TD-DFT) was also performed. The calculated energy level of S1 was 3.12 eV, which was consistent with the experimental results. The natural transition orbitals (NTO) analysis results are shown in Fig. S9, the transition from  $S_0$  to  $S_1$  was also charge transfer (CT) dominated with a high oscillator strength of 0.3876, while the transition from S<sub>0</sub> to T<sub>1</sub> was locally excited dominated.

The ultraviolet–visible (UV–vis) absorption and photoluminescence (PL) spectra of TPA-DPPI in dichloromethane (DCM) solution and neat thin film are shown in Fig. 2a and the corresponding data are summarized in Table S1. The strong absorption band peaked at *ca.* 260 nm could be attributed to the  $\pi$ – $\pi$ \* transition of the benzene rings. While the longer wavelength absorption bands around 360 nm could be assigned to the intramolecular charge transfer (ICT) transition [20,21]. Benefitting from twisted molecular configuration induced weak intermolecular interactions, the absorption spectrum of TPA-DPPI in the film state was very similar to that measured in DCM solution. TPA-DPPI showed a blue emission at 451 nm in DCM and 460 nm in the neat film. The PLQYs in



Scheme 1. The synthetic routes of TPA-DPPI. (i) phenanthrenequinone, benzaldehyde, ammonium acetate, glacial acetic acid, reflux; (ii) 10% Pd/C, 80% hydrazine hydrate, ethanol, reflux; (iii) Pd(PPh<sub>3</sub>)<sub>4</sub>, K<sub>2</sub>CO<sub>3</sub>, THF, reflux; (iv) ammonium acetate, glacial acetic acid, reflux.



Fig. 1. DFT-calculated spatial distributions of the HOMO and LUMO of TPA-DPPI.



Fig. 2. (a) UV-vis absorption and PL spectra of TPA-DPPI measured in DCM solution ( $1.0 \times 10^{-5}$  M) and neat thin film. (b) PL spectra of TPA-DPPI measured in different solvents ( $10^{-5}$  M) at room temperature.

DCM solution and film state were measured to be 0.95 and 0.56 by using an integrating sphere, respectively. In addition, the PL spectra of TPA-DPPI showed an obvious solvatochromic property. The emission peaks red-shifted from 413 nm (in hexane) to 473 nm (in dimethyl sulfoxide) with increasing solvent polarity (Fig. 2b), indicating the excited state of TPA-DPPI is CT-dominated, which is in good agreement with DFT calculation results. The phosphorescence spectrum of TPA-DPPI in dilute toluene measured at 77 K is showed in Fig. S10, and the energy level of the first triplet state was calculated to be 2.68 eV from the onset of the phosphorescence spectrum.

To investigate the hole and electron transporting properties of the compound, single-carrier devices with the configurations of [ITO/NPB (10 nm)/TPA-DPPI (60 nm)/NPB (10 nm)/Al (100 nm)] for hole-only device and [ITO/TPBi (10 nm)/TPA-DPPI (60 nm)/TPBi (10 nm)/LiF (1 nm)/Al (100 nm)] for electron-only device were fabricated [22]. For the hole-only device, only holes could be injected from the indium tin oxide (ITO) anode to the active layer due to a large energy barrier (2.0 eV) from the Al cathode (work function: 4.3 eV) to the neighbouring NPB (LUMO: -2.3 eV) layer. Similarly, in the electron-only device, hole injection from the ITO anode to the neighbouring TPBi layer was prevented due to a large difference (1.4 eV) between the work function of ITO (4.8 eV) and the HOMO level of TPBi (-6.2 eV), and only electrons could be injected. The current density-voltages (J-V) curves of single-carrier devices indicated that TPA-DPPI was a bipolar transporting material and was capable of transporting both electrons and holes (Fig. 3). The balanced carrier transportation contributes to extend exciton recombination region and suppress the efficiency roll off at high current density [23,24].

To investigate the EL performance of TPA-DPPI as an emitter, nondoped device with a configuration of [ITO/NPB (50 nm)/TCTA (5 nm)/TPA-DPPI (30 nm)/TPBi (25 nm)/LiF (1 nm)/Al (100 nm)] was fabricated. The energy-level diagram and molecular structures of the used materials are shown in Fig. 4. In this device, 1,4-bis[(1-naphthylphenyl)amino]-biphenyl (NPB) was used as the hole-transporting layer, 4,4',4"-tri(*N*-carbazolyl)triphenyl-amine (TCTA) was used as the electron-blocking layer, 1,3,5-tris(*N*-phenylbenzimidazol-2-yl)benzene



Fig. 3. Current density versus voltage characteristics of the hole-only and electron-only devices of TPA-DPPI.

(TPBi) was utilized as the electron-transporting and hole-blocking layer, and LiF served as electron-injecting layer, respectively. The characteristic curves and device data are shown in Fig. 5 and Table 1. The device exhibited a pure-blue emission with a CIE coordinates of (0.146, 0.097), which is very close to the NTSC blue standard (CIE: 0.14, 0.08) and displayed little change over a wide range of driving voltages (Fig. S11). The device showed an emission maximum at 460 nm, which was very close to that of the thin-film PL spectrum, suggesting that the EL emission came from the intrinsic emission of TPA-DPPI. The device exhibited a turn-on voltage (Von) of 3.4 V. High device performance with a maximum luminance ( $L_{max}$ ) of 8561 cd m<sup>-2</sup>, a maximum current efficiency (CE<sub>max</sub>) of 4.45 cd A<sup>-1</sup>, a maximum power efficiency (PE<sub>max</sub>) of 4.11  $\text{Im W}^{-1}$ , and a maximum external quantum efficiency (EQE<sub>max</sub>) of 5.20% were achieved, which is comparable with the highest value reported for non-doped pure blue fluorescent OLEDs (Table S2). In addition, the efficiency of the device was still maintained at a high level (CE: 3.16 cd  $A^{-1}$  and EQE: 3.67%) at 1000 cd  $m^{-2}$ , indicating a mild



Fig. 4. Energy level diagrams and the chemical structures of the relevant compounds used in the devices based on TPA-DPPI.



Fig. 5. (a) Current density–voltage–brightness (J–V–L) characteristics; (b) Current efficiencies and power efficiencies versus current density curves; (c) External quantum efficiency versus current density curve; (d) EL spectrum of device based on TPA-DPPI at 100 cd m<sup>-2</sup>.

| Table 1   |  |
|---|--|
| Electroluminescent performance of the OLED based on TPA-DPPI <sup>a</sup> . |  |

| Emitter      | λ <sub>em</sub> /<br>nm | V <sub>on</sub> ∕<br>V | $L_{max}/$ cd $m^{-2}$ | CE <sup>b</sup> /cd<br>A <sup>-1</sup> | PE <sup>b</sup> /lm<br>W <sup>-1</sup> | EQE <sup>b</sup> /<br>% | CIE ( <i>x</i> , y) <sup>c</sup> |
|--------------|-------------------------|------------------------|------------------------|--|--|-------------------------|----------------------------------|
| TPA-<br>DPPI | 460                     | 3.4                    | 8561                   | 4.45,<br>3.16                          | 4.11,<br>1.24                          | 5.20,<br>3.67           | 0.146,<br>0.097                  |

<sup>a</sup> Abbreviation:  $\lambda_{em}$ : emission peak of EL spectrum;  $V_{on}$ : turn-on voltage recorded at the luminance of 1 cd m<sup>-2</sup>;  $L_{max}$ : maximum luminance; CE: current efficiency; PE: power efficiency; EQE: external quantum efficiency; CIE: Commission Internationale de l'Eclairage coordinates.

 $^{\rm b}\,$  Values given in the order of maximum and value at 1000 cd  $m^{-2}$ 

 $^{\rm c}\,$  Recorded at a driving voltage of 5 V.

efficiency roll-off. The small efficiency roll-off was attributed to the bipolar transport nature of TPA-DPPI.

## 3. Conclusions

In summary, we have designed and synthesized a D-A type pure-blue emitting molecule TPA-DPPI. Between TPA and the adjacent PPI chargetransfer process exists, the additional PPI moiety makes the whole molecular with a highly twisted configuration, which contributes to suppress aggregation-induced redshift and quenching of TPA-DPPI in neat film. Eventually, TPA-DPPI exhibits a pure-blue emission at 460 nm and a high PLQY of 0.56 in neat film. The non-doped OLED using TPA-DPPI as the emitting layer shows pure blue emission with a CIE coordinates of (0.146, 0.097) and high device performance with a maximum EQE of 5.20%, which is among the best results reported for non-doped pure blue OLEDs. This study provides an efficient strategy to develop highly efficient blue emitting materials.

#### 4. Experimental section

*Preparation of Materials*: All commercially available reagents were used as received without further purification. All reactions were carried out using Schlenk techniques under a nitrogen atmosphere. 4'-(diphenylamino)biphenyl-4-carbaldehyde (TPAPh-CHO) were synthesized according to literature methods [25,26].

Synthesis of 1-(4-nitrophenyl)-2-phenyl-1H-phenanthro[9,10-d]imidazole (NO<sub>2</sub>-PPI): A mixture of phenanthrenequinone (416 mg, 2 mmol), benzaldehyde (212 mg, 2 mmol), 4-nitroaniline (1.38 g, 10 mmol), ammonium acetate (616 mg, 8 mmol) and glacial acetic acid (20 mL) was refluxed for 5 h under nitrogen atmosphere. After cooling to room temperature, the reaction mixture was poured into methanol with stirring. The separated solid was filtered off, washed with water and dried to give a yellow-green solid. The solid was then purified by column chromatography on silica gel using DCM as the eluent to give the product. Yield: 75%. <sup>1</sup>H NMR (300 MHz, DMSO-d<sub>6</sub>)  $\delta$  8.96 (d, *J* = 8.2 Hz, 1H), 8.90 (d, *J* = 8.2 Hz, 1H), 8.69 (dd, *J* = 7.9, 1.3 Hz, 1H), 8.54–8.46 (m, 2H), 8.09–8.01 (m, 2H), 7.79 (dd, *J* = 10.9, 4.0 Hz, 1H), 7.75–7.67 (m, 1H), 7.57 (m, 3H), 7.43–7.35 (m, 4H), 7.10 (d, *J* = 7.4 Hz, 1H), ESI-MS (M): *m/z*: 416.21 [M]<sup>+</sup> (calcd: 415.13).

Synthesis of 4-(2-phenyl-1H-phenanthro[9,10-d]imidazole-1-yl)aniline (NH<sub>2</sub>-PPI): The suspension of NO<sub>2</sub>-PPI (4.15 g, 10 mmol) and 10% Pd/C (250 mg) in 150 mL ethanol was heated to refluxing, and 80% hydrazine hydrate(10 mL) was dripped in half an hour. The mixture was stirred for 6 h, and then cooled to room temperature. The solution was poured into distilled water and neutralized with aqueous HCl to give a white precipitate, which was separated by filtration and then recrystallized from dimethylformamide (DMF)/water to give white solid. Yield: 94%. <sup>1</sup>H NMR (500 MHz, DMSO-d<sub>6</sub>)  $\delta$  8.91 (d, *J* = 8.4 Hz, 1H), 8.86 (d, *J* = 8.4 Hz, 1H), 8.67 (d, *J* = 7.8 Hz, 1H), 7.76 (t, *J* = 7.4 Hz, 1H), 7.67 (dd, *J* = 6.5, 2.4 Hz, 3H), 7.56 (t, *J* = 7.3 Hz, 1H), 7.47–7.31 (m, 5H), 7.24 (d, *J* = 8.5 Hz, 2H), 6.76 (d, *J* = 8.5 Hz, 2H), 5.66 (s, 2H). ESI-MS (M): *m/z*: 386.11 [M]<sup>+</sup> (calcd: 385.16).

Synthesis of N,N-diphenyl-4'-(1-(4-(2-phenyl-1H-phenanthro[9,10-d] imidazole-1-yl)phenyl)-1H-phenanthro[9,10-d]imidazole-2-yl)biphenyl-4amine (TPA-DPPI): A mixture of 9,10-phenanthraquinone (416 mg, 2 mmol), NH<sub>2</sub>-PPI (1.16 g, 3 mmol), TPAPh-CHO (0.70 g, 2 mmol), ammonium acetate (1.54 g, 20 mmol) and glacial acetic acid (20 mL) was refluxed for 5 h under nitrogen atmosphere. After cooling to room temperature, the reaction mixture was poured into methanol with stirring. The separated solid was filtered off, washed with water and dried to give a yellow-green solid. The solid was then purified by column chromatography on silica gel using CH<sub>2</sub>Cl<sub>2</sub> as the eluent to give the product. Yield: 68%. <sup>1</sup>H NMR (500 MHz, DMSO-*d*<sub>6</sub>)  $\delta$  9.10–8.83 (m, 5H), 8.77–8.68 (m, 2H), 8.13–7.97 (m, 4H), 7.88–7.51 (m, 16H), 7.44–7.27 (m, 6H), 7.27–7.06 (m, 9H), 7.06–7.00 (m, 1H). ESI-MS (M): *m/z*: 907.25 [M]<sup>+</sup> (calcd: 905.35). Anal. Calcd (%) for C<sub>66</sub>H<sub>43</sub>N<sub>5</sub>: C, 87.49; H, 4.78; N, 7.73. Found: C, 87.51; H, 5.20; N, 7.43.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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#### Appendix A. Supplementary data

N. Fei, Q. Wei, L. Cao, Y. Bai, H. Ji, R. Peng, L. Huang, H. Shiyou, Z. Ge,

A symmetric nonpolar blue AIEgen as nondoped fluorescent OLED emitter with low efficiency roll-off, Org. Electron. 78 (2020), 105574.
[3] Y. Jia, S. Wu, Y. Zhang, S. Fan, X. Zhao, H. Liu, X. Dong, S. Wang, X. Li, Achieving

displays: present status and future perspectives, Light Sci. Appl. 9 (2020) 105.

[1] Y. Huang, E.-L. Hsiang, M.-Y. Deng, S.-T. Wu, Mini-LED, Micro-LED and OLED

- non-doped deep-blue OLEDs by applying bipolar imidazole derivatives, Org. Electron. 69 (2019) 289–296
- [4] M.A. Baldo, S. Lamansky, P.E. Burrows, M.E. Thompson, S.R. Forrest, Very highefficiency green organic light-emitting devices based on electrophosphorescence, Appl. Phys. Lett. 75 (1999) 4–6.
- [5] M.A. Baldo, D.F. O'Brien, Y. You, A. Shoustikov, S. Sibley, M.E. Thompson, S. R. Forrest, Highly efficient phosphorescent emission from organic electroluminescent devices, Nature 395 (1998) 151–154.
- [6] M.A. Baldo, M.E. Thompson, S.R. Forrest, High-efficiency fluorescent organic lightemitting devices using a phosphorescent sensitizer, Nature 403 (2000) 750–753.
- [7] H. Uoyama, K. Goushi, K. Shizu, H. Nomura, C. Adachi, Highly efficient organic light-emitting diodes from delayed fluorescence, Nature 492 (2012) 234–238.
- [8] X. Liang, Z.L. Tu, Y.X. Zheng, Thermally activated delayed fluorescence materials: towards realization of high efficiency through strategic small molecular design, Chem. Eur J. 25 (2019) 5623–5642.
- [9] J.-H. Lee, C.-H. Chen, P.-H. Lee, H.-Y. Lin, M.-k. Leung, T.-L. Chiu, C.-F. Lin, Blue organic light-emitting diodes: current status, challenges, and future outlook, J. Mater. Chem. C 7 (2019) 5874–5888.
- [10] Y. Liu, C. Li, Z. Ren, S. Yan, M.R. Bryce, All-organic thermally activated delayed fluorescence materials for organic light-emitting diodes, Nat. Rev. Mater. 3 (2018) 1–20.
- [11] K. Ivaniuk, V. Cherpak, P. Stakhira, Z. Hotra, B. Minaev, G. Baryshnikov, E. Stromylo, D. Volyniuk, J.V. Grazulevicius, A. Lazauskas, S. Tamulevicius, B. Witulski, M.E. Light, P. Gawrys, R.J. Whitby, G. Wiosna-Salyga, B. Luszczynska, Highly luminous sky-blue organic light-emitting diodes based on the bis[(1,2) (5,6)]indoloanthracene emissive layer, J. Phys. Chem. C 120 (2016) 6206–6217.
- [12] T. Hatakeyama, K. Shiren, K. Nakajima, S. Nomura, S. Nakatsuka, K. Kinoshita, J. Ni, Y. Ono, T. Ikuta, Ultrapure blue thermally activated delayed fluorescence molecules: efficient HOMO–LUMO separation by the multiple resonance effect, Adv. Mater. 28 (2016) 2777–2781.
- [13] C. Fu, S. Luo, Z. Li, X. Ai, Z. Pang, C. Li, K. Chen, L. Zhou, F. Li, Y. Huang, Z. Lu, Highly efficient deep-blue OLEDs based on hybridized local and charge-transfer emitters bearing pyrene as the structural unit, Chem. Commun. 55 (2019) 6317–6320.
- [14] Z.-L. Zhu, S.-F. Ni, W.-C. Chen, M. Chen, J.-J. Zhu, Y. Yuan, Q.-X. Tong, F.-L. Wong, C.-S. Lee, Tuning electrical properties of phenanthroimidazole derivatives to construct multifunctional deep-blue electroluminescent materials, J. Mater. Chem. C 6 (2018) 3584–3592.
- [15] H. Zhang, J. Zeng, W. Luo, H. Wu, C. Zeng, K. Zhang, W. Feng, Z. Wang, Z. Zhao, B. Z. Tang, Synergistic tuning of the optical and electrical performance of AIEgens with a hybridized local and charge-transfer excited state, J. Mater. Chem. C 7 (2019) 6359–6368.
- [16] B. Liu, Z.-W. Yu, D. He, Z.-L. Zhu, J. Zheng, Y.-D. Yu, W.-F. Xie, Q.-X. Tong, C.-S. Lee, D. Ambipolar, A type bifunctional materials with hybridized local and charge-transfer excited state for high performance electroluminescence with EQE of 7.20% and CIEy ~ 0.06, J. Mater. Chem. C 5 (2017) 5402–5410.
- [17] X. Chen, H. Zhang, H.J. Tan, L. Yang, P. Qin, X.H. Zheng, S.S. Tang, Y. Liu, Q. X. Tong, Rational molecular design of multifunctional blue material based on phenanthroimidazole derivatives, Chem. Eur J. (2021), https://doi.org/10.1002/chem.202005214.
- [18] H.W. Bae, G.W. Kim, R. Lampande, J.H. Park, I.J. Ko, H.J. Yu, C.Y. Lee, J.H. Kwon, Efficiency enhancement in fluorescent deep-blue OLEDs by boosting singlet exciton generation through triplet fusion and charge recombination rate, Org. Electron. 70 (2019) 1–6.
- [19] C. Li, J. Wei, J. Han, Z. Li, X. Song, Z. Zhang, J. Zhang, Y. Wang, Efficient deep-blue OLEDs based on phenanthro[9,10-d]imidazole-containing emitters with AIE and bipolar transporting properties, J. Mater. Chem. C 4 (2016) 10120–10129.
- [20] C. Li, J. Wei, X. Song, K. Ye, H. Zhang, J. Zhang, Y. Wang, Non-doped luminescent material based organic light-emitting devices displaying high brightness under very low driving voltage, J. Mater. Chem. C 4 (2016) 7013–7019.
- [21] C. Li, Z. Li, J. Liang, H. Luo, Y. Liu, J. Wei, Y. Wang, A twisted phenanthroimidazole based molecule with high triplet energy as a host material for high efficiency phosphorescent OLEDs, J. Mater. Chem. C 6 (2018) 12888–12895.
- [22] W.Y. Hung, P.Y. Chiang, S.W. Lin, W.C. Tang, Y.T. Chen, S.H. Liu, P.T. Chou, Y. T. Hung, K.T. Wong, Balance the carrier mobility to achieve high performance exciplex OLED using a triazine-based acceptor, ACS Appl. Mater. Interfaces 8 (2016) 4811–4818.
- [23] B. Liang, J. Wang, Y. Cui, J. Wei, Y. Wang, Benzimidazole-triazine based exciplex films as emitters and hosts to construct highly efficient OLEDs with a small efficiency roll-off, J. Mater. Chem. C 8 (2020) 2700–2708.
- [24] B. Liang, Z. Yu, X. Zhuang, J. Wang, J. Wei, K. Ye, Z. Zhang, Y. Liu, Y. Wang, Achieving high-performance pure-red electrophosphorescent iridium(III)

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References

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complexes based on optimizing ancillary ligands, Chem. Eur J. 26 (2020) 4410–4418.
[25] M.-Y. Lai, C.-H. Chen, W.-S. Huang, J.T. Lin, T.-H. Ke, L.-Y. Chen, M.-H. Tsai, C.-

- 25] M.-Y. Lai, C.-H. Chen, W.-S. Huang, J.T. Lin, T.-H. Ke, L.-Y. Chen, M.-H. Tsai, C.-C. Wu, Benzimidazole/amine-based compounds capable of ambipolar transport for application in single-layer blue-emitting OLEDs and as hosts for phosphorescent emitters, Angew. Chem. Int. Ed. 47 (2008) 581–585.
- [26] M.J. Cho, S.J. Kim, S.H. Yoon, J. Shin, T.R. Hong, H.J. Kim, Y.H. Son, J.S. Kang, H. A. Um, T.W. Lee, J.-K. Bin, B.S. Lee, J.H. Yang, G.S. Chae, J.H. Kwon, D.H. Choi, New bipolar host materials for realizing blue phosphorescent organic light-emitting diodes with high efficiency at 1000 cd/m<sup>2</sup>, ACS Appl. Mater. Interfaces 6 (2014) 19808–19815.