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Graphical abstract



A new bipolar host material based on triphenylamine, fluorene and 1,2-diphenyl-1H-benzo[d]imidazole moieties, N,N-diphenyl-4-(9-phenyl-2-(4-(1-phenyl-1H-benzo[d]imidazol-2-yl)phenyl)-9H-fluoren-9-yl)aniline (DPPBIPFA) was designed and synthesized via Suzuki coupling. The material exhibited an excellent thermal stability (T_d = 475 °C), electrochemical stability and high triplet energy (2.68 eV), which can be used as bipolar host in OLEDs.

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A Novel Host Material with High Thermal Stability for Green Electrophosphorescent Device

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Abstract

A new bipolar host material based on triphenylamine, fluorene and 1,2-diphenyl-1H-benzo[d]imidazole moieties,

N,N-diphenyl-4-(9-phenyl-2-(4-(1-phenyl-1H-benzo[d]imidazol-2-yl)phenyl)-9H-fluo ren-9-yl)aniline (DPPBIPFA), was designed and synthesized. The as-synthesized material was well characterized by ¹H and ¹³C NMR spectroscopy, high-resolution mass spectrometry and thermogravimetric analysis, respectively. The photophysical and electrochemical properties of the material were also studied. The material exhibited an excellent thermal stability ($T_d = 475$ °C), electrochemical stability and high triplet energy (2.68 eV). A green phosphorescent organic light-emitting diode (PhOLED) device based on DPPBIPFA as the host material and Ir(ppy)₃ as the dopant was fabricated, which displayed favorable electrophosphorescent properties with a turn-on voltage of 3.75 V, a maximum brightness of 1685 cd/m² and a maximum current efficiency of 4.26 cd/A. **Key words:** bipolar host material; high thermal stability; phosphorescence; doped OLED

1. Introduction

In the past decades, organic light-emitting diodes (OLEDs) have drawn much attention due to their applications in full-color flat-panel displays and solid-state lighting sources.¹⁻³ Phosphorescent organic light-emitting diodes (PhOLEDs) can theoretically achieve 100% internal quantum efficiency, which has attracted considerable attention since the first report on applying the phosphorescent host-dopant system to address the issues of concentration quenching and the triplet-triplet annihilation, etc.⁴⁻⁶ In the PhOLEDs, the phosphorescent hosts play a vital role which serve as the recombination center for electrons and holes to generate the electronically excited states.⁷⁻⁸ Recently, bipolar hosts have aroused considerable interest because they can balance the mobility of electrons and holes, generate broad charge recombination zones, and simplify device structure, thus boosting the device performance obviously.⁹⁻¹¹ For example, Hsu et al. in 2009 reported a phosphine-oxide-containing bipolar host for application in a blue device with maximum power efficiency of 26.2 lm/W.¹² Chen et al. developed a hybrid indole/triazine bipolar host, exhibiting a high glass transition temperature of 124 °C and maximum external quantum efficiency of 17.5% for a red PHOLED.¹³ Tian et al. recently designed and synthesized a spiro-annulated host with a high decomposition temperature of 427 °C and a high triplet energy of 2.9 eV.¹⁴

An ideal host material should meet the following intrinsic requirements: (i) a triplet energy gap (E_T) larger than that of the dopant to prevent reverse energy transfer from the guest back to the host; (ii) good carrier transporting properties to balance the charge flux and reduce the driving voltage; (iii) good thermal and morphological stability to prolong the device's operational lifetime.¹⁵⁻¹⁷

In this paper, we designed and synthesized a novel host material N,N-diphenyl-4-(9-phenyl-2-(4-(1-phenyl-1H-benzo[d]imidazol-2-yl)phenyl)-9H-fluo ren-9-yl)aniline (**DPPBIPFA**) based on triphenylamine, carbazole and

1,2-diphenyl-1H-benzo[d]imidazole moieties, which can be used as the host matrix to fabricate the green-light PhOLED with $Ir(ppy)_3$ as dopant. The DPPBIPFA exhibits three important features: (i) bipolarity, resulting from the presence of the D- π -A system, (ii) a value of E_T as high as 2.68 eV, (iii) a sterically bulky and hindered structure which can prevent the aggregation of guest emitters and provide excellent thermal stability (onset decomposition temperature (T_d) = 475 °C). Due to the above favorable features, the material DPPBIPFA can be used as a host to fabricate green PhOLEDs with phosphorescent dopants, such as $Ir(ppy)_3$.¹⁸⁻²⁰

2. Experimental

2.1. Synthesis of

N,N-diphenyl-4-(9-phenyl-2-(4-(1-phenyl-1H-benzo[d]imidazol-2

-yl)phenyl)-9H-fluoren-9-yl)aniline (DPPBIPFA)

Solvents were dried using standard methods. All other reagents were used as received from commercial sources, unless stated otherwise.

In a dry flask, phenylmagnesium bromide in THF (15 mL, 12 mmol) was added dropwisely to a solution of 2-bromo-9-fluorenone (2.58 g, 10 mmol) in THF at -78 °C under a nitrogen atmosphere. The mixture was allowed to warm to room temperature followed by stirring for 12 h. After neutralization by aqueous HCl and then extraction with ethyl acetate, the organic layer was separated out and dried over anhydrous Na₂SO₄. Then the solvent was removed by using a rotary evaporator. The crude material was purified by silica gel column chromatography using a petroleum and dichloromethane mixture (v:v = 1:1) as the eluent to obtain the desired product (**1**) as a white solid (2.3 g, 89%). ¹H NMR (CDCl₃, 400 MHz, δ /ppm): 7.67-7.69 (d, J = 7.6 Hz, 2H) , 7.33-7.41 (m, 6H), 7.24-7.29 (m, 5H), 2.51 (s, 1H).

In a flask, five drops of BF_3 ethanol solution was added dropwisely to a solution of compound (1) (1.1 g, 3.3 mmol) and triphenylamine (1.5 g, 6.1 mmol) in CH_2Cl_2 (15 mL) at room temperature. After stirring for 2 h, ethanol was added to quench the reaction. The solvent was evaporated and the resulting crude material was purified by silica gel column chromatography using a petroleum and dichloromethane

mixture (v:v = 3:1) as the eluent to give the desired product (**2**) as a white solid (1.0 g, 56%). ¹H NMR (CDCl₃, 400 MHz, δ /ppm): 7.71-7.73 (d, J = 7.6 Hz, 1H), 7.61-7.63 (d, J = 8 Hz, 1H), 7.47-7.53 (m, 2H), 7.20-7.40 (m, 12H), 6.90-7.08 (m, 10H).

In a flask. compound (2)(0.56)1 mmol), g, (4-(1-phenyl-1H-benzo[d]imidazol-2-yl)phenyl)boronic acid (0.37 g, 1.2 mmol), K₂CO₃ (0.66 g, 4 mmol), Pd(PPh₃)₄ (30 mg, 0.03 mmol, 99.8%) were dissolved in water (4 ml) and THF (12 ml). The mixture was bubbled with nitrogen and then allowed to reflux for 6 h. Then the solution was cooled to room temperature and poured into water followed by extraction with CH₂Cl₂. The organic layer was dried over anhydrous $MgSO_4$ and concentrated using a rotary evaporator. The crude material was purified by silica gel column chromatography using a petroleum and dichloromethane mixture (v:v=1:1) to give the target compound DPPBIPFA as a white solid (0.45 g, 60%). ¹H NMR (CDCl₃, 400 MHz, δ/ppm): 7.89-7.91 (d, J = 8Hz, 1H), 7.79-7.81 (d, J = 8Hz, 1H), 7.76-7.78 (d, J = 8Hz, 1H), 7.59-7.64 (m, 4H), 7.49-7.55 (m, 5H), 7.41-7.42 (d, J = 4Hz, 1H), 7.32-7.39 (m, 4H), 7.19-7.30 (m, 11H), 7.05-7.08 (m, 6H), 6.89-7.04 (m, 5H). ¹³C NMR (CDCl₃, 101 MHz): δ 152.14, 152.00, 151.75, 147.59, 146.29, 145.86, 142.99, 142.06, 139.86, 139.51, 139.16, 137.33, 137.05, 129.94, 129.74, 129.16, 128.87, 128.61, 128.25, 128.10, 127.83, 127.50, 127.46, 126.87, 126.62, 126.22, 124.64, 124.41, 123.34, 123.01, 122.96, 122.79, 120.49, 120.26, 119.76, 110.40. HRMS (ESI, m/z): [M+H]⁺ calcd for C₅₆H₃₉N₃, 754.3222, found 754.3214.

2.2. Characterization of materials

¹H and ¹³C NMR spectra were recorded using a Switzerland Bruker spectrometer relative to tetramethylsilane (TMS) as the internal standard. Elemental analyses were performed using a Vario EL elemental analyzer. Differential scanning calorimetry (DSC) was performed using a DSC Q2000, operated at a heating rate of 10 °C/min and a cooling rate of 50 °C/min; the glass transition temperature (T_g) was determined from the second heating scan. Thermogravimetric analysis (TGA) was undertaken using a Netzsch TG 209, the thermal stability of sample was determined under a

nitrogen atmosphere by measuring the weight loss while heating at a rate of 20 ^oC/min. UV-vis absorption spectrum was measured by using a Hitachi U-3900 spectrophotometer. The photoluminescence (PL) spectrum was obtained by using a Fluromax-4 spectrophotometer in diluted THF solution. The low-temperature phosphorescence spectrum was obtained using a composite spectrometer incorporating a monochromator (F-7000 FL Spectrophotometer) coupled with a liquid charge-coupled (F-7000 nitrogen cooled device (CCD) detector FL Spectrophotometer). Cyclic voltammetry (CV) measurement was performed using an Autolab/PG STAT302 electrochemical analyzer operated at a scan rate of 50 mV/s through a one-compartment electrolysis cell consisting of a platinum wire as working electrode, a platinum electrode as counter electrode, and a calomel electrode as reference electrode. Tetrabutylammonium perchlorate dissolved in acetonitrile was used as a supporting electrolyte $(0.1 \text{ mol } \text{L}^{-1})$.

2.3. OLED fabrication and measurements

The EL device was fabricated through vacuum thermal evaporation technology according to the methods modified from our previous approach. Device with an area of 3 mm \times 3 mm was fabricated by vacuum deposition (at 1 \times 10⁻⁶ torr) of functional layers onto indium tin oxide (ITO) glass substrate which has a sheet resistance of 25 Ω /square. The ITO glass substrate was cleaned with deionized water, acetone, ethanol in turn and dried in the oven at 120 °C. Then, the clear ITO glass substrate was treated with oxygen plasma for 8 min. The PEDOT:PSS layer was spin-coated onto the ITO substrate in air, and then allowed to anneal at 120 °C for 15 min in a glovebox. All the other organic layers were deposited at a rate of 1.0 Å/s sequentially. The cathode was completed through thermal deposition of LiF (10 Å) at a deposition rate of 0.1 Å/s; then Al metal (200 nm) was deposited through thermal evaporation at a rate of 5.0 Å/s. The voltage-current-luminance relationships of the OLEDs were recorded with a Keithley 2400 Source Meter. The EL spectrum was obtained using a Hitachi F4500 luminescence The brightness-current-voltage spectrometer. (B-I-V)characterizations were carried out with a 3645 DC power supply combined with a

1980A spot photometer and were recorded simultaneously. All measurements were done at room temperature under ambient conditions.

3. Results and discussion

3.1 Synthesis and characterization

The synthetic route of the bipolar material DPPBIPFA is illustrated in Scheme 1. Intermediate compound (1) was firstly synthesized from the starting materials 2-bromo-9-fluorenone and phenylmagnesium bromide by Grignard reaction, which then undergo coupling with triphenylamine to generate intermediate (2) with Lewis acid BF_3 as the catalyst. Finally, the target compound was synthesized by the Suzuki reaction of compound (2) and (4-(1-phenyl-1H-benzo[d]imidazol-2-yl)phenyl)boronic acid. All the new compounds were obtained with satisfactory yield and well characterized by ¹H and ¹³C NMR spectroscopy and high-resolution mass spectrometry (HRMS).



Scheme 1 The synthetic route of DPPBIPFA.

3.2 Photophysical properties

The UV-vis absorption, photoluminescence (at room temperature) and phosphorescence spectra (at 77 K) of DPPBIPFA in THF (1×10^{-5} M) at room temperature are shown in Fig. 1. As we can see from the absorption spectrum of DPPBIPFA, there is a broad absorption band with the maximum peak centered at about 320 nm which can be assigned to the fluorene-centered n- π^* transition.²¹ The

optical energy bandgap (E_g) can be calculated from the absorption band edge of the absorption spectrum which is approximately 3.26 eV. The PL spectrum of DPPBIPFA implies that this novel bipolar host material exhibits a broad fluorescence emission band between 350 and 610 nm with an emission maximum (λ_{em}) at 460 nm. In order to examine the triplet energy (E_T) of DPPBIPFA, we performed the measurement of low temperature phosphorescent spectrum. By calculation with the phosphorescence spectrum of DPPBIPFA at 77K in THF, E_T of DPPBIPFA was determined to be 2.68 eV, implying that DPPBIPFA is suitable for application in green PhOLEDs as a host material.^{22,23}



Fig.1 Absorption, photoluminescence (at room temperature) and phosphorescence spectra (at 77 K) of DPPBIPFA in THF (1×10^{-5} M).

3.3 Electrochemical properties and energy level

Cyclic voltammetry (CV) was performed to study the electrochemical properties of the bipolar host material DPPBIPFA. The CV curve was recorded in a one-compartment electrolysis cell with platinum wire as working electrode, platinum counter electrode, calomel electrode as reference electrode, plate as tetrabutylammonium perchlorate acetonitrile solution (0.1 mol L⁻¹) as the supporting electrolyte and ferrocene as the external reference. It exhibits a well-behaved reversible oxidation wave with the oxidation potential $E_{ox} = +1.00$ V, which is assigned to the oxidation of the fluorene moiety. The HOMO energy level can be

calculated with the empirical equation: $E_{\text{HOMO}} = (E_{ox} + 4.40) \text{ eV}$, where E_{ox} is the onset oxidation potential. Thus, the HOMO enegy level of DPPBIPFA was finally determined to be -5.40 eV. As mentioned before, the optical energy E_g is estimated to be 3.26 eV from the absorption edge of the absorption spectrum, hence the LUMO energy level of DPPBIPFA was calculated to be -2.14 eV by the formula $E_{\text{LUMO}} = E_{\text{HOMO}} + E_g$.²⁴ All the electrochemical data are summarized in Table 1.

Table 1 Physical properties of DPPBIPFA.

$\lambda_{abs}{}^a(nm)$	$\lambda_{em}(nm)$	HOMO ^b (eV)	LUMO (eV)	$E_{g}^{c}(eV)$	E _T (eV)	$T_d^{d}(^{\mathrm{o}}\mathrm{C})$	$T_{g}(^{o}C)$
241, 282, 320	466	-5.40	-2.14	3.26	2.68	400	167

^aMeasured in tetrahydrofuran (THF). ^bMeasured versus ferrocene, the HOMO and LUMO energy levels were determined using the following equations: $E_{HOMO} = (E_{ox} + 4.40) \text{ eV}, E_{LUMO} = E_{HOMO} + E_{g}$. ^cObtained from onset of the absorption spectrum by extrapolation (E_g = 1240/ $\lambda_{set on}$). ^dMeasured by TGA at heating rate of 10 ^oC min⁻¹

3.4 Thermal properties

The thermal property of DPPBIPFA was examined by TGA and differential scanning calorimetry (DSC) under an N₂ atmosphere, respectively (see Fig. 2). The endothermic glass transition (T_g) of DPPBIPFA was found to be 156 °C. As indicated by the TGA curve of DPPBIPFA, it exhibits excellent thermal stability with the onset decomposition temperature (T_{db} corresponding to 5% weight loss) as high as 475 °C, implying that DPPBIPFA is favorable for fabrication of OLED devices by vacuum thermal evaporation technology due to its excellent thermal stability.²⁵



Fig. 2 (a) DSC curve of DPPBIPFA and (b) TGA curve of DPPBIPFA.

3.5 Electroluminescence

In order to evaluate the electroluminescent property of DPPBIPFA, we fabricated green PhOLED with DPPBIPFA as the host material and Ir(ppy)₃ (8 wt%) as the dopant. The device structure was as follows: ITO/Pedot:PSS (50 nm)/NPB (60 nm)/Ir(ppy)₃ (8 wt%):host (40 nm)/Bphen (10 nm)/TAZ (20nm)/LiF (1 nm)/Al (see Fig. 3). Pedot:PSS was used as hole-injection and hole-transporting layer; NPB was chosen as hole-tansporting layer; Bphen and TAZ was applied as the electron-transporting layer, meanwhile, Bphen can also reduce the electron

transporting barrier from TAZ to DPPBIPFA.²⁶ Fig. 4 displays the current density–voltage–luminance curve and the current efficiency–current density curve of the device, respectively. Table 2 summarizes the electroluminescent characteristics of the device which exhibits a turn-on voltage of 3.75 V, a maximum luminance efficiency of 4.26 cd/A and a maximum luminance of 1685 cd/m².



Fig. 3 Energy-level diagram of the materials used in the devices.

The EL spectra of the above device at different applied voltages are shown in Fig. 4(a). The maximum emission peak is found at 516 nm with the Commission Internationale de L'Eclairage (CIE) coordinates of (0.33, 0.61). The shape of the EL spectra did not show much change with the increase of the applied voltages. However, the EL intensity enhanced greatly, because high voltage help improve the charge

mobility which in turn promotes the exciton recombination for emission.²⁷

The good performance of the device could be attributed to the excellent thermal stability of the functional materials, which enhances the capability of forming stable amorphous thin film. It should be pointed out that the electroluminescent performance was obtained under ordinary laboratory where the device is not packaged. The device performance could be further improved by optimization of the processing conditions.²⁸



Fig. 4 (a) The EL spectra, (b) the current density-voltage-luminance curve and (c) the current efficiency-current density curve of the devices.

Host	Turn-on	Turn-on Max. Luminance ^c		λ_{EL}	$CIE(x, y)^{e}$	
	Voltage ⁶ (V)	(cd/m ²)	(cd/A, Im/W)	(nm) ^u		
DPPBIPFA	3.75	1685	4.26, 2.43	516	(0.33, 0.61)	

Table 2 Characteristics of OLED^a

^aITO/Pedot:PSS (50 nm)/NPB (60 nm)/Ir(ppy)₃ (8 wt%):host (40 nm)/Bphen (10 nm)/TAZ (20 nm)/LiF (1 nm)/Al. ^bTurn-on voltage at 1 cd/cm². ^cMaximum values. ^dMaximum EL emission peak. ^eCommission Internationale de L'Eclairage(CIE) at 8V.

Conclusions

In novel material host summary, а N,N-diphenyl-4-(9-phenyl-2-(4-(1-phenyl-1H-benzo[d]imidazol-2-yl)phenyl)-9H-flu oren-9-yl)aniline (DPPBIPFA) has been designed and synthesized using a simple method. The structure of DPPBIPFA was fully characterized by various spectroscopic methods. The thermal, electrochemical and photophysical properties of DPPBIPFA were also studied in detail. High onset decomposition temperature of DPPBIPFA implies that it is very thermally stable. In order to examine the electroluminescent property of DPPBIPFA, a green OLED device with DPPBIPFA as host and Ir(ppy)₃ as dopant was fabricated by vacuum thermal evaporation method. The turn-on voltage, maximum luminance and maximum luminance efficiency of the as-prepared green device are 3.75 V, 1685 cd/m² and 4.26 cd/A, respectively, which implies that this novel bipolar host material DPPBIPFA has a promising application potential in commercial OLED devices. Further optimization of the OLED devices based on DPPBIPFA is in progress.

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References

- 1. Tang, C. W.; VanSlyke, S. A. Appl. Phys. Lett. 1987, 51, 913-915.
- 2. Shi, J.; Tang, C. W. Appl. Phys. Lett. 1997, 70, 1665-1667.
- 3. Baldo, M. A.; O'brien, D. F.; You, Y. Nature. 1998, 395, 151-154.
- 4. Baldo, M. A.; Lamansky, S.; Burrows, P. E. Appl. Phys. Lett. 1999, 75, 4-6.
- 5. Adachi, C.; Kwong, R. C.; Djurovich, P. Appl. Phys. Lett. 2001, 79, 2082-2084.
- D'Andrade, B. W.; Baldo, M. A.; Adachi, C. Appl. Phys. Lett. 2001, 79, 1045-1047.
- 7. Ulbricht, C.; Beyer, B.; Friebe, C. Adv. Mater. 2009, 21, 4418-4441.
- 8. Holmes, R. J.; D'Andrade, B. W.; Forrest, S. R. Appl. Phys. Lett. 2003, 83, 3818-3820.
- 9. Adachi, C.; Kwong, R. C.; Djurovich, P. Appl. Phys. Lett. 2001, 79, 2082-2084.
- 10. Cai, X.; Padmaperuma, A. B.; Sapochak, L. S. Appl. Phys. Lett. 2008, 92, 083308-083308-3.
- 11. Li, W.; Qiao, J.; Duan, L.; Wang, L. D.; Qiu, Y. Terahedron. 2007, 63, 10161-10168.
- 12. Hsu, F.-M.; Chien, C.-H.; Shih, P.-I.; Shu, C.-F. Chem. Mater. 2009, 21, 1017-1022.
- 13. Chen, Y.; Xie, J.; Wang, Z.; Cao, J.; Chen, H.; Huang, J.; Zhang, J.; Su, J. *Dyes. Pigm.* **2016**, *124*, 188-195.
- 14. Tian, G.; Liang, W.; Chen, Y.; Xiang, N.; Dong, Q.; Huang, J.; Su, J. Dyes. *Pigm.* **2016**, *216*, 296-302.
- Tao, Y. T.; Wang, Q.; Yang, C. L.; Wang, Q.; Zhang, Z. Q.; Zou, T. T.; Qin, J. G.; Ma, D. G. Angew. Chem., Int. Ed. 2008, 47, 8104–8107.

- 16. Holder, E.; Langeveld, B. M. W.; Schubert, U. S. Adv. Mater. 2005, 17, 1109–1121.
- 17. Aizawa, N.; Pu, Y. J.; Sasabe, H.; Kido, J. Org. Electron. 2012, 13, 2235–2242.
- Hung, W. Y.; Chi, L. C.; Chen, W. J.; Mondal, E.; Chou, S. H.; Wong, K. T.; Chi, Y. J. Mater. Chem. 2011, 21, 19249–19256.
- 19. Jeon, S. O.; Lee, J. Y. J. Mater. Chem. 2012, 22, 7239-7244.
- 20. Doda, T.; Shirota, Y. J. Am. Chem. Soc. 1998, 120, 9714–9715.
- Shi, H. P.; Yuan, J. D.; Wu, X. H.; Dong, X. Q.; Fang, L.; Miao, Y. Q.; Wang, H.; Cheng, F. Q. New J. Chem. 2014, 38, 2368-2378.
- Zhou, G. J.; Ho, C. L.; Wong, W. Y.; Wang, Q.; Ma, D. G.; Wang, L. X.; Lin, Z. Y.; Marder, T. B.; Beeby, A. Adv. Funct. Mater. 2008, 18, 499–511.
- 23. Chiu, C. W.; Kim, Y.; Gabbai, F. P. J. Am. Chem. Soc. 2009, 131, 60-61.
- 24. Noda, T.; Ogawa, H.; Shirota, Y. Adv. Mater. 1999, 11, 283-285.
- 25. Zheng, Z. W.; Dong, Q. C.; Gou, L.; Su, J. H.; Huang, J. H. J. Mater. Chem. C. 2014, 2, 9858-9865.
- 26. Matsushima, T.; Jin, G.; Murata, H. J. Appl. Phys. 2008, 104, 054501-1-5.
- 27. Huang, J. H.; Su, J. H.; Li, X.; Lam, M. K.; Fung, K. M.; Fan, H. H.; Cheah, K. W.; Chen, C. H.; Tian, H. *J. Mater. Chem.* **2011**, *21*, 2957-2964.
- 28. Sakuda, E.; Ando, Y.; Ito, A.; Kitamura, N. J. Phys. Chem. A. 2010, 114, 9144–9150.