Dyes and Pigments 101 (2014) 9–14

Contents lists available at ScienceDirect

Dyes and Pigments

journal homepage: www.elsevier.com/locate/dyepig

A novel, bipolar host based on triazine for efficient solution-processed single-layer green phosphorescent organic light-emitting diodes

Bin Huang [a,b], Wei Jiang [a,*], Jinan Tang [a], Xinxin Ban [a], Ruigang Zhu [b], Huange Xu [a], Wen Yang [a], Yueming Sun [a,*]

[a] *School of Chemistry and Chemical Engineering, Southeast University, Nanjing 211189, Jiangsu, PR China*
[b] *Department of Chemical and Pharmaceutical Engineering of Southeast University Chengxian College, Nanjing 210088, Jiangsu, PR China*

ARTICLE INFO

Article history:
Received 1 July 2013
Received in revised form
16 August 2013
Accepted 11 September 2013
Available online 25 September 2013

Keywords:
OLEDs
Solution-processed
Electrophosphorescence
Triazine
Bipolar
Host material

ABSTRACT

A novel N-phenyl carbazole substituted 2, 4,6-trisphenyl-triazine host material(TPCPZ) for solution processed green phosphorescent organic light-emitting devices (PhOLEDs) was synthesized by a Suzuki-cross coupling reaction. The optical, electrochemical and thermal properties of TPCPZ have been characterized. TPCPZ exhibits a high glass transition temperature of 165 °C and a triplet energy of 2.63 eV. The appropriate HOMO energy level (−5.39 eV) and LUMO energy level (−2.16 eV) matching with the HOMO energy level of PEDOT:PSS(−5.35 eV) and the LUMO energy level of Cs_2CO_3/Al bilayer cathode (−2.2 eV), facilitate the transfer of holes and electrons. The solution-processed single-layer device using TPCPZ as the host for fac-tris(2-(4-phenylpyridine)iridium ($Ir(ppy)_3$) exhibited a low turn-on voltage of 3.5 V, a maximum current efficiency of 20.8 cd A^{-1} and a maximum luminance of 18,000 cd m^{-2}. These results demonstrated that TPCPZ as a host material is advantageous for fabrication of highly efficient single-layer green PhOLEDs.

1. Introduction

Since efficient phosphorescent emitters for organic light-emitting diodes (PhOLEDs) was discovered by Forrest's group, tremendous efforts have been made in the development of highly efficient devices [1–5]. In PhOLEDs, the emitting layer consists of a phosphorescent dye which is doped into a host material to avoid concentration quenching and to optimize the charge balance. High efficiencies are obtained only when the energy is efficiently transferred from the host to the phosphorescent dye. To achieve efficient electrophosphorescence, the choice of host is of vital importance [6].Generally, the triplet energy of the host material is higher than that of the guest. For efficient OLEDs, well balanced charge carrier transport and a broad recombined zone are desirable. In general, the electron mobility of many host materials is much lower than the hole mobility because of the fact that they consist electron donors such as aromatic amines, carbazoles. This task is mostly solved by a design of a bipolar material [7,8]. Introduction of strong electron donors such as aromatic amines or carbazoles [9] to electron accepting N-heterocycles like pyridine [10–12], oxadiazole [13–16], phenathroline [17–19], benzimidazole [20–24], is well described. Triazines, are known to be good electron conductors and their derivatives have been used as electron transport layers in OLEDs [4,25–28].Recently, some bipolar host materials based on triazines for PhOLEDs are reported [29–34]. A series of donor substituted 1,3,5-triazine derivatives as host for blue or green PhOLEDs show good performance.

In recent years, many groups are devoted to improve the performance of solution-processed PhOLEDs which are highly desirable to simplify the fabrication process and reduce the cost of larger area displays [35–44]. Even though polymer light-emitting diodes can be easily fabricated by solution casting, they are generally difficult to synthesize and purify for electronic devices. Therefore, it is a good strategy to develop OLEDs based on solution-processed small molecules. However, the largest challenge for small molecules lies in the poor solubility accompanied by the tendency to crystallize and failure to form high quality films. Consequently, it is of significant importance to design and synthesize amorphous small molecules with high purity and solubility. To date, few works reported on bipolar host based on 1, 3,5-triazine for solution-processed PhOLEDs.

In this work, a bipolar host composed of electron-transporting 2, 4,6-trisphenyl-triazine and hole-transporting N-phenyl carbazole,

---

[*] Corresponding authors. Tel./fax: +86 25 52090621.
E-mail address: 101011462@seu.edu.cn (W. Jiang).

0143-7208/$ – see front matter Crown Copyright © 2013 Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.dyepig.2013.09.017

namely 2, 4,6-tris (3-((9-phenyl) carbazol-3-yl)-phenyl) -triazine(TPCPZ) is designed and synthesized. The dipolar nature of TPCPZ can promote the strong π–π intermolecular stacking of molecules in the solid state, which can facilitate high charge transport. Moreover, the electron-donating N-phenyl carbazole moieties are conjugated to the electron accepting 2, 4,6-trisphenyl-triazine core; the donor-acceptor intramolecular interaction tends to decrease the energy gap. TPCPZ has a triplet energy of 2.62 eV, which make it suitable as host material for green phosphorescent emitters. The material exhibits high thermal stability and good sublimation properties. The glass transition temperature of 165 °C ensures morphological stability of the host-guest emission layer during the operation of the device. Additionally, TPCPZ has good solubility in common solvents such as CH_2Cl_2, $CHCl_3$, 1,2-dichloroethane et al., which make it suitable for the fabrication of solution-processed PhOLEDs. The single-layer device with TPCPZ as host has low turn-on voltage of 3.5 V, a high maximum luminance efficiency of 20.8 cd A^{-1} and maximum luminance of 18,000 cd m^{-2} in a solution-processed green phosphorescent OLED using an emitter of fac-tris(2-(4-phenylpyridine)iridium ($Ir(ppy)_3$)).

2. Experimental

2.1. General

All reactants and solvents were purchased from commercial sources and used without further purification. ^1H NMR and ^{13}C NMR spectra were recorded on a Bruker ARX300 NMR spectrometer with $Si(CH_3)_4$ as the internal standard. Elemental analysis was performed on an Elementar Vario EL CHN elemental analyzer. Mass spectra were obtained using a Thermo Electron Corporation Finnigan LTQ mass spectrometer. UV–vis absorption spectra were recorded with a spectrophotometer (Agilent 8453) and PL spectra were recorded with a fluorospectrophotometer (Jobin Yvon, FluoroMax-3). Thermogravimetric analysis (TGA) was performed using a Netzsch simultaneous thermal analyzer (STA) system (STA 409PC) under dry nitrogen atmosphere at a heating rate of 10 °C min^{-1}. Glass transition temperature was recorded by differential scanning calorimetry (DSC) at a heating rate of 10 °C min^{-1} with a thermal analysis instrument (DSC 2910 modulated calorimeter). Cyclic voltammetry measurements were performed on a Princeton Applied Research potentiostat/galvanostat model 283 voltammetric analyzer in CH_2Cl_2 solutions (10^{-3} M) at a scan rate of 100 mV s^{-1} with a platinum plate as the working electrode, a silver wire as the pseudo-reference electrode, and a platinum wire as the counter electrode. The supporting electrolyte was tetrabutylammonium hexafluorophosphate (0.1 M) and ferrocene was selected as the internal standard. The solutions were bubbled with a constant argon flow for 10 min before measurements.

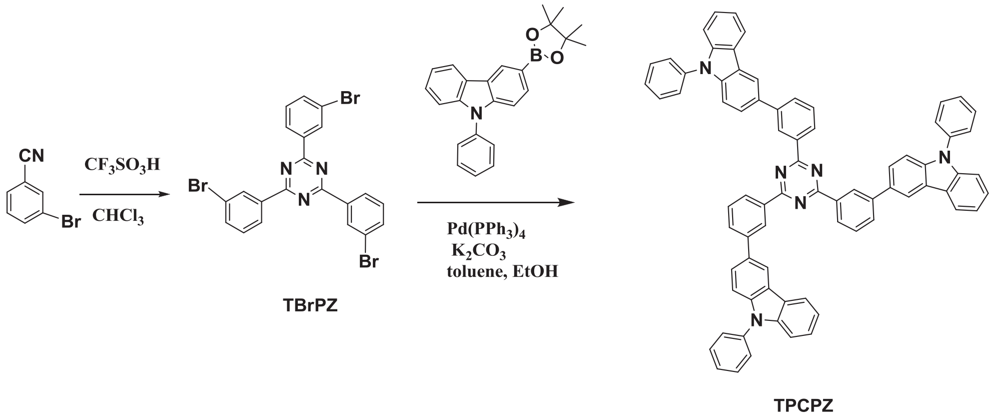
DFT calculations of TPCPZ were performed using the Gaussian 03 program package. The calculation was optimized at the B3LYP/6-31G(d) level of theory. The molecular orbitals were visualized using Gaussview [45].

2.2. Synthesis of 2,4,6-tris(3-((9- phenyl)carbazol-3-yl)-phenyl)-triazine(TPCPZ)

To a solution of 2,4,6-tris(3-bromophenyl)-triazine (TBrPZ) (0.546 g, 1.0 mmol) and N-phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolane-2-yl)-6H-carbazole (1.107 g, 3.0 mmol) in 20 mL of toluene and 4 mL of ethanol was added 2 mL of 2.0 M aqueous K_2CO_3 solution. The reaction mixture was then purged with nitrogen for 10 min before adding tetrakis(triphenylphosphine) palladium(0) (0.055 g, 0.048 mmol). After refluxing for 24 h under nitrogen, the resulting mixture was cooled to room temperature and then poured into water and extracted with 60 mL (3 × 20 mL) CH_2Cl_2. The combined organic phase was then washed with 20 mL (2 × 10 mL) saturated aqueous NaCl solution and dried with anhydrous Na_2SO_4. After removal of the solvent by rotary evaporation, the residue was purified by silica gel column chromatography to afford TPCPZ as a white solid. Yield: 0.60 g (58.08%).^1H NMR(300 MHz, $CDCl_3$): δ(ppm) 9.17 (s, 3H), 8.81–8.78 (d, 3H), 8.50 (s, 3H), 8.16–8.19 (d, 3H), 7.96–7.98(d, 3H), 7.80–7.83(m, 3H), 7.67–7.73 (t, 3H), 7.65–7.56 (m, 12H), 7.52–7.43 (m, 6H), 7.40–7.35 (m, 6H), 7.16–7.20 (m, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) δ(ppm):109.50, 109.78, 118.67, 119.71, 120.03, 123.06, 123.62, 125.18, 125.80, 126.71, 126.97, 127.14, 127.39, 128.78, 129.54, 131.16, 132.68, 136.51, 137.29, 140.18, 141.02, 142.18, 171.57. MS (MALDI-TOF) [*m*/*z*]: calcd for $C_{75}H_{48}N_6$, 1033.22; found, 1033.48. Anal. Calcd. for $C_{75}H_{48}N_6$ (%): C, 87.18; H, 4.68; N 8.13. Found: C, 87.34; H, 4.72; N 8.38.

2.3. Device fabrication and performance measurements

The solution-processed single-layer device using TPCPZ as host with a configuration ITO/PEDOT:PSS (40 nm)/TPCPZ: $Ir(ppy)_3$ (90 wt%:10 wt%,100 nm)/Cs_2CO_3 (2 nm)/Al (120 nm) has been fabricated by spin-coating. In a general procedure, indium-tin oxide (ITO)-coated glass substrates were pre-cleaned carefully and treated by UV ozone for 4 min. A 40 nm Poly(3,4-ethylenedioxythio phene) doped with Poly(styrene-4-sulfonate)(PEDOT:PSS) aqueous solution was spin coated onto the ITO substrate and baked at 210 °C for 10 min. The substrates were then taken into a nitrogen glove box, where $Ir(ppy)_3$-doped TPCPZ layer was spin coated onto the



Scheme 1. Synthetic route of TPCPZ.

PEDOT:PSS layer from 1,2-dichloroethane solution and annealed at 120 °C for 30 min. The substrate was then transferred into an evaporation chamber, where the Cs_2CO_3/Al bilayer cathode was evaporated at evaporation rates of 0.2 and 10 Å/s for Cs_2CO_3 and Al, respectively, under a pressure of 1×10^{-3} Pa. The current-voltage-brightness characteristics of the device were characterized with Keithley 4200 semiconductor characterization system. The electroluminescent spectra were collected with a Photo Research PR705 Spectrophotometer. All measurements of the devices were carried out in ambient atmosphere without further encapsulations.

3. Results and discussion

3.1. Synthesis and characterization

Scheme 1 shows the synthetic routes and structure of the newly synthesized TPCPZ. 2,4,6-tris(3-bromophenyl)-triazine (TBrPZ) was synthesized according to the literature procedure[4]. N-phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolane-2-yl)-6H-carbazole was synthesized according to the literature procedure with carbazole as start material [46]. Subsequently, Suzuki-cross coupling reaction of TBrPZ with N-phenyl-3-(4, 4, 5,5-tetramethyl-1, 3, 2-dioxaborolane-2-yl)-6H-carbazole led to TPCPZ with a yield of 58.08%. Finally, the product was purified by the silica column method and recrystallization from n-hexane/CH_2Cl_2, yielding the very pure white powders. ^1H NMR, ^{13}C NMR, matrix-assisted laser desorption ionization time-of-flight (MALDI-TOF) mass spectrometry, and elemental analysis were employed to confirm the chemical structure of TPCPZ in the experimental section.

3.2. Thermal properties of the host materials

The thermal properties TPCPZ were investigated by thermal gravimetric analyses (TGA) and differential scanning calorimetry (DSC) under nitrogen atmosphere at a heating rate of 10 °C min^{-1}. As shown in Fig.1, TGA measurement reveals its high thermal decomposition temperature (Td), corresponding to 5% weight-loss of 559 °C. The DSC trace exhibits a clear glass transition temperature(Tg) of 165 °C during the second heating scans. The thermal analysis results clearly demonstrate the very high thermal stability of TPCPZ, which facilitates the forming of amorphous films through solution processing.

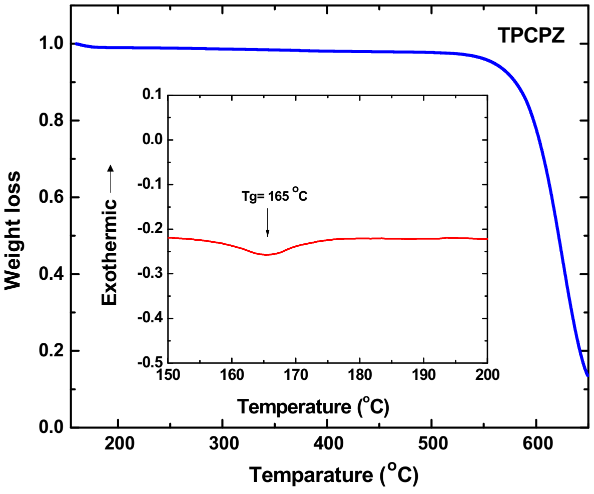


Fig. 1. TGA traces (blue curve) of TPCPZ recorded at a heating rate of 10 °C min^{-1}, DSC (red curve) measurement recorded at a heating rate of 10 °C min^{-1}.

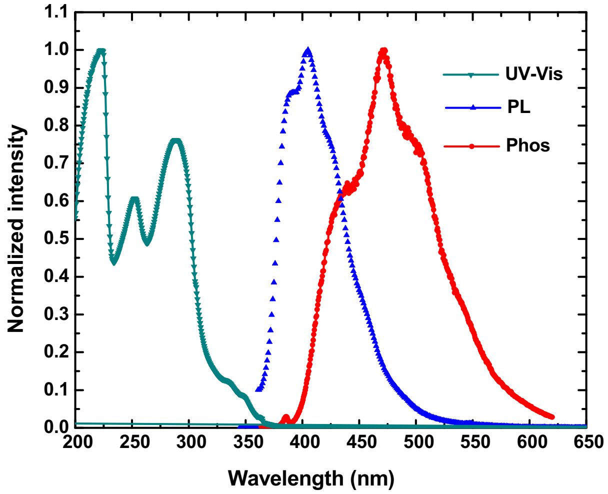


Fig. 2. Normalized UV–vis absorption (Abs, green curve), photoluminescence (PL, blue curve) and phosphorescence (77 K) (PH, red curve) spectra of TPCPZ.

3.3. Optical properties of the host materials

Fig. 2 depicts the UV–vis absorption and photoluminescence (PL) spectra of TPCPZ in hexane. Four major absorption peaks locate at 223, 252, 289, 335 nm in the absorption spectra, while the emission peaks appear at 405 nm in the PL spectra. The absorption peaks at 223, 252 nm can be attributed to the $\pi-\pi^*$ and $n-\pi^*$ transitions of the central 2, 4,6-trisphenyl-triazine and outer N-phenyl. The absorption peaks at 289 nm, 335 nm can be attributed to the $\pi-\pi^*$ and $n-\pi^*$ transitions of the outer carbazole of TPCPZ. From the absorption edge of the UV–vis absorption, the optical bandgap (Eg) of TPCPZ can be estimated to be 3.23 eV. The phosphorescence spectra measured from a frozen 2-methyltetrahydrofuran matrix at 77 K are also shown in Fig. 2. The triplet energy of TPCPZ was determined to the value of 2.63 eV by the highest energy 0–0 phosphorescent emission, which is sufficiency high enough to serve as the appropriate host for $Ir(ppy)_3$.

3.4. Electrochemical analysis and theoretical calculations of the host material

The electrochemical properties TPCPZ were studied in solution through cyclic voltammetry (CV) using tetrabutylammonium

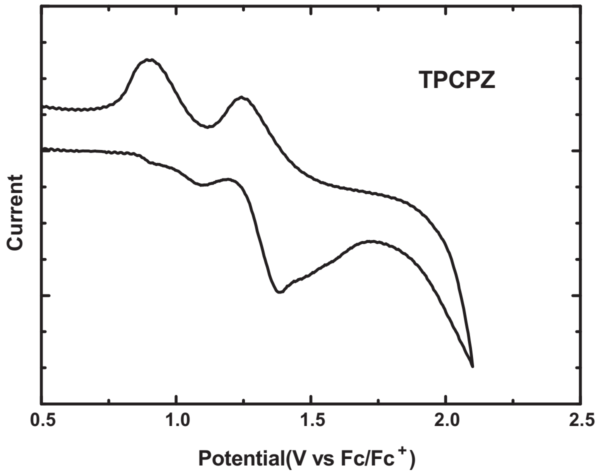


Fig. 3. Oxidation part of the CV curves of TPCPZ in CH_2Cl_2 solutions (10^{-3} M).

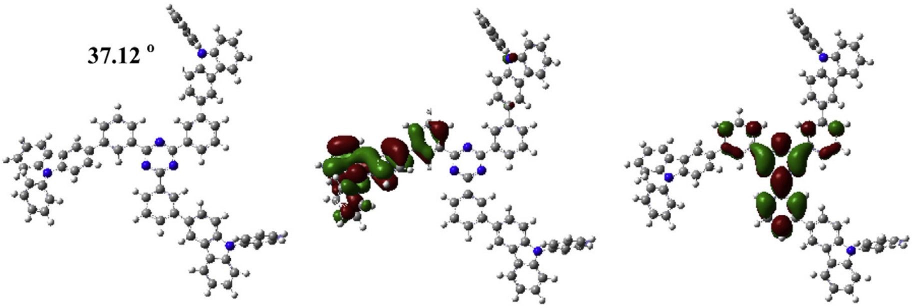


Fig. 4. Optimized geometries and calculated HOMO and LUMO density maps for TPCPZ according to DFT calculations at B3LYP/6-31* level.

hexafluorophosphate ($TBAPF_6$) as the supporting electrolyte and ferrocene as the internal standard. The highest occupied molecular orbital (HOMO) energy level of TPCPZ was characterized by the electrochemical cyclic voltammetry (CV) (Fig.3). During the anodic scan in CH_2Cl_2, TPCPZ exhibited reversible oxidation process, which can be assigned to the oxidation of electron-donating carbazole moiety, with the onset potential of 1.18 eV. No reduction wave was detected. On the basis of the onset potential for oxidation, the HOMO energy level was estimated to be −5.39 eV, the HOMO energy level approach the work function of PEDOT(−5.2 eV), which allows in a low barrier of hole injection. The LUMO energy level of TPCPZ estimated from the HOMO energy level and Eg is −2.16 eV, which matches the LUMO energy level of Cs_2CO_3/Al bilayer cathode (−2.2 eV), facilitates electrons injection.

DFT calculations were performed to understand the physical properties of the TPCPZ at themo-Lecular level. As shown in Fig.4, the outer layer N-phenyl carbazole units are significantly twisted with inner 2, 4,6-trisphenyl-triazine unit, resulting in a non-planar structure in the molecule. These geometrical characteristics can effectively prevent intermolecular interactions between systems and thus suppress molecular recrystallization and limit the extent of conjugation between the central core and branches, which improves the morphological stability of thin film of TPCPZ. The LUMO level of TPCPZ is localized predominantly on the 2, 4,6-trisphenyl-triazine unit, while the HOMO level is distributed over the outer layer N-phenyl carbazole fragments.

3.5. *Electroluminescent properties*

The single-layer green electrophosphorescent device with TPCPZ as the host and $Ir(ppy)_3$ as the dopant with the configuration of ITO/PEDOT:PSS/TPCPZ:$Ir(ppy)_3$/Cs_2CO_3/Al has been fabricated by spin-coating. As shown in Fig.5, the electroluminescence (EL) spectra of TPCPZ based device is identical with the CIE

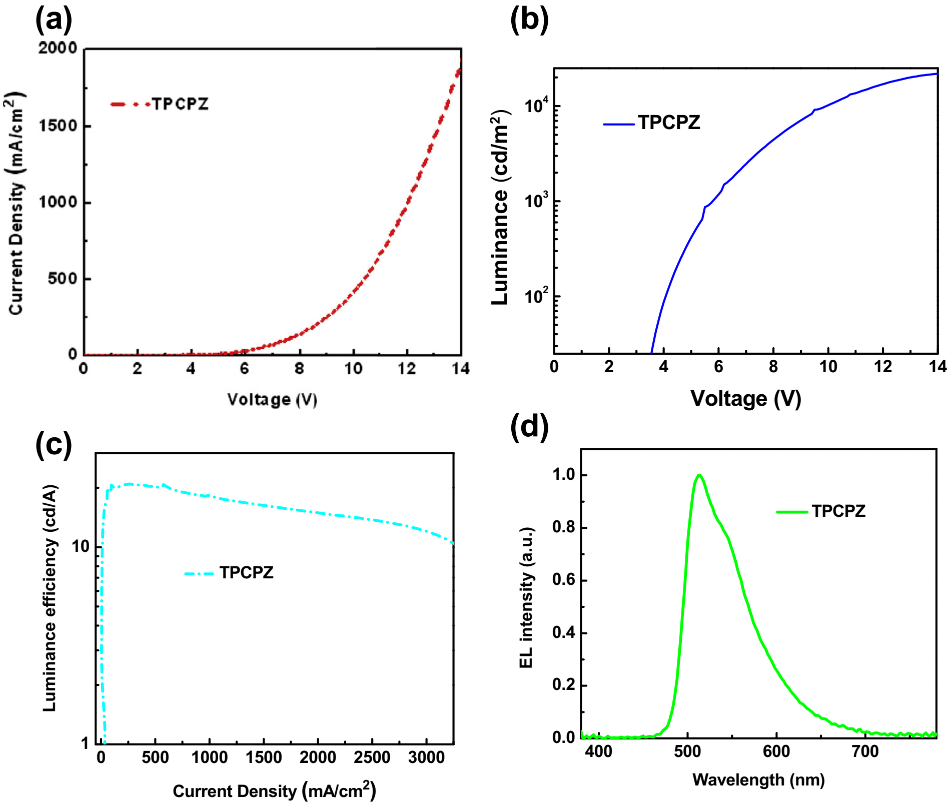


Fig. 5. (a) Current-voltage (b) Luminance-voltage characteristics (c) Luminance efficiency versus current density plots of the devices. (d) The normalized EL spectra of devices at a driving voltage of 10 V.

coordinates of (0.315, 0.605), corresponding to the emission of Ir(ppy)$_3$, and indicate the efficient energy transfer from the host to Ir(ppy)$_3$. The *J*–*V* characteristic curves of the device demonstrate the turn-on voltage is only 3.5 V. On one hand, the low turn-on voltage of TPCPZ based device is most likely due to their high-lying HOMO energy level and low-lying LUMO energy level, which matched with the HOMO energy level of PEDOT:PSS(−5.35 eV) and the LUMO energy level of Cs_2CO_3/Al bilayer cathode (−2.2 eV), thereby facilitated holes and electrons injection of the device. On the other hand, the bipolar nature of TPCPZ make it have good and balanced charge carrier transport properties for the hole–electron recombination process and confinement of the exciton formation zone in the emissive layer. As revealed in Fig. 5, the maximum LE value of this single-layer green-emitting device was 20.8 cd A^{-1} and a maximum luminance was 18,000 cd m^{-2}.

4. Conclusions

In summary, we have designed and synthesized a novel bipolar solution-processable triazine-based host material. TPCPZ exhibits high glass transition temperature and high thermal stability. Results from CV and computational calculations show that TPCPZ has high-lying HOMO energy level and low-lying LUMO energy level. The triplet energy of TPCPZ is 2.63 eV. Utilizing TPCPZ as host material, highly efficient solution-processed single-layer green PhOLED has been achieved with low turn-on voltage of 3.5 V, a maximum current efficiency of 20.8 cd A^{-1} and a maximum luminance of 18,000 cd m^{-2}.

Acknowledgments

The authors thank Dr. Zhao Yan for OLEDs fabrication and measurement. This work was supported by the National Natural Science Foundation of China (Grant No.51103023 and 21173042), the National Basic Research Program of China (Grant No.2013CB932900), the Research Fund for Graduate Innovation Project of Jiangsu Province (No. CXZZ13_0090) and the science and technology support program (industry) project of Jiangsu province (BE 2013118).

References

[1] Baldo MA, O'Brien DF, You Y, Shoustikov A, Sibley S, Thompson ME, et al. Highly efficient phosphorescent emission from organic electroluminescent devices. Nature 1998;395:151–4.
[2] Reineke S, Lindner F, Schwartz G, Seidler N, Walzer K, Lüeesem B, et al. White organic light-emitting diodes with fluorescent tube efficiency. Nature 2009;459:234–9.
[3] Xiao LX, Chen ZJ, Qu B, Luo JX, Kong S, Gong QH, et al. Recent progresses on materials for electrophosphorescent organic light-emitting devices. Adv Mater 2011;23:926–52.
[4] Su SJ, Sasabe H, Pu YJ, Nakayama K, Kido J. Tuning energy levels of electron-transport materials by nitrogen orientation for electrophosphorescent devices with an 'ideal' operating volta. Adv Mater 2010;22:3311–6.
[5] Han CM, Zhang ZS, Xu H, Li J, Xie GH, Chen RF, et al. Controllably tuning excited-state energy in ternary hosts for ultra low-voltage-driven blue electrophosphorescence. Angew Chem Int Ed 2012;51:10104–8.
[6] Tao YT, Yang CL, Qin JG. Organic host materials for phosphorescent organic light-emitting diodes. Chem Soc Rev 2011;40:2943–70.
[7] Chaskar A, Chen HF, Wong KT. Bipolar host materials: a chemical approach for highly efficient electrophosphorescent devices. Adv Mater 2011;23:3876–95.
[8] Kim DW, Coropceanu V, Bredas JL. Design of efficient ambipolar host materials for organic blue electrophosphorescence: theoretical characterization of hosts based on carbazole derivatives. J Am Chem Soc 2011;133:17895–900.
[9] D'Andrade BW, Datta S, Forrest SR, Djurovich P, Polikarpov E, Thompson ME. Relationship between the ionization and oxidation potentials of molecular organic semiconductors. Org Electron 2005;6:11–20.
[10] Williams EL, Haavisto K, Li J, Jabbour GE. Excimer-based white phosphorescent organic light-emitting diodes with nearly 100% internal quantum efficiency. Adv Mater 2007;19:197–202.
[11] Su SJ, Sasabe H, Takeda T, Kido J. Pyridine-containing bipolar host materials for highly efficient blue phosphorescent OLEDs. Chem Mater 2008;20:1691–3.
[12] Su SJ, Cai C, Kido J. RGB phosphorescent organic light-emitting diodes by using host materials with heterocyclic cores: effect of nitrogen atom orientations. Chem Mater 2011;23:274–84.
[13] Tao Y, Wang Q, Ao L, Zhong C, Qin J, Yang C, et al. Molecular design of host materials based on triphenylamine/oxadiazole hybrids for excellent deep-red phosphorescent organic light-emitting diodes. J Mater Chem 2010;20:1759–65.
[14] Tao Y, Wang Q, Ao L, Zhong C, Qin J, Yang C, et al. Multifunctional triphenylamine/oxadiazole hybrid as host and exciton-blocking material: high efficiency green phosphorescent OLEDs using easily available and common materials. Adv Funct Mater 2010;20:2923–9.
[15] Tao Y, Wang Q, Yang C, Wang Q, Zhang Z, Zou T, et al. A simple carbazole/oxadiazole hybrid molecule: an excellent bipolar host for green and red phosphorescent OLEDs. Angew Chem Int Ed 2008;47:8104–7.
[16] He Z, Kan CW, Ho CL, Wong WY, Chui CH, Tong KL, et al. Light-emitting dyes derived from bifunctional chromophores of diarylamine and oxadiazole: synthesis, crystal structure, photophysics and electroluminescence. Dyes Pigments 2011;88:333–43.
[17] Gao ZQ, Luo M, Sun XH, Tam HL, Wong MS, Mi BX, et al. New host containing bipolar carrier transport moiety for high-efficiency electrophosphorescence at low voltages. Adv Mater 2009;21:688–92.
[18] Ge ZY, Hayakawa T, Ando S, Ueda M, Akiike T, Miyamoto H, et al. Synthesis and properties of 3,8-bis(4-(9H-carbazol-9-yl)phenyl)-1,10-phenanthroline for phosphorescent OLEDs. Chem Lett 2008;37:262–3.
[19] Ge ZY, Hayakawa T, Ando S, Ueda M, Akiike T, Miyamoto H, et al. Novel bipolar bathophenanthroline containing hosts for highly efficient phosphorescent OLEDs. Org Lett 2008;10:421–4.
[20] Li YQ, Fung MK, Xie Z, Lee ST, Hung LS, Shi J. An efficient pure blue organic light-emitting device with low driving voltages. Adv Mater 2002;14:1317–21.
[21] Ge ZY, Hayakawa T, Ando S, Ueda M, Akiike T, Miyamoto H, et al. Spin-coated highly efficient phosphorescent organic light-emitting diodes based on bipolar triphenylamine-benzimidazole derivatives. Adv Funct Mater 2008;18:584–90.
[22] Lai MY, Chen CH, Huang WS, Lin JT, Ke TH, Chen LY, et al. 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 2008;47:581–5.
[23] Chen CH, Huang WS, Lai MY, Tsao WC, Lin JT, Wu YH, et al. Versatile, benzimidazole/amine-based ambipolar compounds for electroluminescent applications: single-layer, blue, fluorescent OLEDs, hosts for single-Layer, phosphorescent OLEDs. Adv Funct Mater 2009;19:2661–70.
[24] Huang H, Yang X, Pan Biao, Wang Lei, Chen J, Ma D, et al. Benzimidazole-carbazole- based bipolar hosts for high efficiency blue and white electrophosphorescence applications. J Mater Chem 2012;22:13223–30.
[25] Richard A, Klenklera HA, Tranc A, Popovic DZ, Xu G. High electron mobility triazine for lower driving voltage and higher efficiency organic light emitting devices. Org Electron 2008;9:285–90.
[26] Matsushima T, Takamori M, Miyashita Y, Honma Y, Tanaka T, Aihara H, et al. High electron mobility layers of triazines for improving driving voltages, power conversion efficiencies, and operational stability of organic light-emitting diodes. Org Electron 2010;11:16–22.
[27] Sun C, Hudson ZM, Helander MG, Lu ZH, Wang S. A polyboryl-functionalized triazine as an electron transport material for OLEDs. Organometallics 2011;30:5552–5.
[28] Chen HF, Wang TC, Lin SW, Hung WY, Dai HC, Chiu HC, et al. Peripheral modification of 1,3,5-triazine based electron-transporting host materials for sky blue, green, yellow, red, and white electrophosphorescent devices. J Mater Chem 2012;22:15620–7.
[29] Inomata H, Goushi K, Masuko T, Konno T, Imai T, Sasabe H, et al. High-efficiency organic electrophosphorescent diodes using 1, 3, 5-triazine electron transport materials. Chem Mater 2004;16:1285–91.
[30] Son K, Yahiro M, Imai T, Yoshizaki H, Adachi C. Analyzing bipolar carrier transport characteristics of diarylamino-substituted heterocyclic compounds in organic light-emitting diodes by probing electroluminescence spectra. Chem Mater 2008;20:4439–46.
[31] Rothmann MM, Haneder S, Como ED, Lennartz C, Schildknecht C, Strohriegl P. Donor-substituted 1,3,5-triazines as host materials for blue phosphorescent organic light-emitting diodes. Chem Mater 2010;22:2403–10.
[32] Rothmann MM, Fuchs E, Schildknecht C, Langer N, Lennartz C, Münster I, et al. Designing a bipolar host material for blue phosphorescent OLEDs: phenoxy-carbazole substituted triazine. Org Electron 2011;12:1192–7.
[33] An ZF, Chen RF, Yin J, Xie GH, Shi HF, Tsuboi T, et al. Conjugated asymmetric donor-substituted 1,3,5-triazines: new host materials for blue phosphorescent organic light-emitting diodes. Chem – Eur J 2011;17:10871–8.
[34] Su SJ, Cai CH, Tankmatsu J, Kido J. A host material with a small singlet–triplet exchange energy for phosphorescent organic light-emitting diodes: guest, host and exciplex emission. Org Electron 2012;13:1937–47.
[35] Arias AC, MacKenzie JD, McCulloch I, Rivnay J, Salleo A. Materials and applications for large area electronics: solution-based approaches. Chem Rev 2010;110:3–24.

[36] Hou LD, Duan L, Qiao J, Li W, Zhang DQ, Qiu Y. Efficient single layer solution-processed blue-emitting electrophosphorescent devices based on a small-molecule host. Appl Phys Lett 2008;92(26):263301.

[37] Ye SH, Liu YQ, Lu K, Wu WP, Du CY, Liu Y, et al. An alternative approach to constructing solution processable multifunctional materials: their structure, properties, and application in high-performance organic light-emitting diodes. Adv Funct Mater 2010;20:3125–35.

[38] Ye SH, Chen JM, Lu K, Wu WP, Du CY, Liu Y, et al. Solution-processed solid solution of a novel carbazole derivative for high-performance blue phosphorescent organic light-emitting diodes. Adv Mater 2010;22:4167–71.

[39] Li W, Qiao J, Duan L, Wang LD, Qiu Y. Novel fluorene/carbazole hybrids with steric bulk as host materials for blue organic electrophosphorescent devices. Tetrahedron 2006;63:10161–8.

[40] Jiang W, Ge ZJ, Cai PY, Huang B, Dai YQ, Sun YM, et al. Star-shaped dendritic hosts based on carbazole moieties for highly efficient blue phosphorescent OLEDs. J Mater Chem 2012;22:12016–22.

[41] Lee CW, Lee JY. High quantum efficiency in solution and vacuum processed blue phosphorescent organic light emitting diodes using a novel benzofuropyridine-based bipolar host material. Adv Mater 2013;25:596–600.

[42] Jiang W, Duan L, Qiao J, Dong GF, Wang LD, Qiu Y. Tuning of charge balance in bipolar host materials for highly efficient solution-processed phosphorescent devices. Org Lett 2011;13:3146–9.

[43] Gong SL, Fu Q, Wang Q, Yang CL, Zhong C, Qin JG, et al. Highly efficient deep-blue electrophosphorescence enabled by solution-processed bipolar tetraarylsilane host with both a high triplet energy and a high-lying HOMO level. Adv Mater 2011;23:4956–9.

[44] Jiang W, Duan L, Qiao J, Dong GF, Zhang DQ, Wang LD, et al. Novel carbazole/pyridine-based host material for solution-processed blue phosphorescent organic light-emitting devices. Dyes Pigments 2012;92:891–6.

[45] Gaussian 03 (Revision B.05). Wallingford CT: Gaussian, Inc.; 2004.

[46] Cho I, Kim SH, Kim JH, Park S, Park SY. Highly efficient and stable deep-blue emitting anthracene-derived molecular glass for versatile types of non-doped OLED applications. J Mater Chem 2012;22:123–9.