Solution-Processible Blue Fluorescent Dendrimers with Carbazole/Diphenylamine Hybrid Dendrons for Power-Efficient Organic Light-Emitting Diodes

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ABSTRACT: Two blue fluorescent dendrimers named PVAC2 and PVACA have been newly synthesized and investigated, where the carbazole/diphenylamine hybrid dendron is adopted instead of oligocarbazole. Compared with the reference dendrimer PVCt3, the emission maxima of PVAC2 and PVACA are found to be red-shifted accompanied by a slight reduction of the photoluminescence quantum yield in films. Most importantly, the highest occupied molecular orbital level is elevated from −5.35 eV of PVCt3 to −5.20 eV of PVAC2 and −4.95 eV of PVACA. Because of the favored hole injection, the turn-on voltage is accordingly decreased from 3.6 to 3.2 and 2.6 V. The value of PVACA is even lower than the theoretical limit of 2.78 V. In addition, PVAC2 exhibited the best nondoped device performance, showing a nearly doubled power efficiency of 4.80 lm/W relative to PVCt3 (2.37 lm/W). The results clearly indicate that dendron engineering is also a promising strategy to develop solution-processible blue fluorescent dendrimers capable of being used for power-efficient organic light-emitting diodes.

1. INTRODUCTION

Wet method is believed to be a more favorable technique than vacuum deposition for the preparation of organic light-emitting diodes (OLEDs) so as to realize low-cost and large-area solid-state lighting sources and flat-panel displays.1−3 In this case, the used electroluminescent materials include small molecules,4−7 polymers,8,9 and dendrimers.10−15 Among them, dendrimers possess excellent solution processibility due to their inherent branched topology structures. Meanwhile, the emissive core (either fluorescence,1,2,12 phosphorescence14,15 or TADF16,17) is often surrounded by the periphery dendrons to prevent the unwanted self-aggregation and concentration-quenching in neat films. These features make dendrimers suitable for efficient solution-processed nondoped OLEDs.

Nowadays, a series of dendrimers have been successfully demonstrated, whose emission colors can range from blue to red.18−27 However, we observe that the turn-on voltage, especially for blue-emitting ones, is still far away from the driving voltage theoretical limit (Eo/e: corresponds to the optical bandgap divided by the electron charge).28 To solve such a problem, we have, for the first time, proposed dendron engineering in self-host blue phosphorescent dendrimers to develop power-efficient nondoped OLEDs that can be driven at low voltage which is adjacent the theoretical limit. Instead of oligocarbazole, the carbazole/diphenylamine hybrid is used to enhance the highest occupied molecular orbital (HOMO) level of the dendron.29 Owing to the favored hole injection and exciton formation, the operating voltage at 1, 100, and 1000 cd/m² is greatly decreased from 4.9/5.8/7.4 V of B-CzCz with oligocarbazole dendrons to 2.7/3.4/4.4 V of B-CzTA with carbazole/diphenylamine hybrid dendrons, respectively. Also the corresponding maximum power efficiency is nearly doubled from 15.6 to 30.3 lm/W.

Promoted by this interesting result, herein, we further extend the dendron engineering strategy from phosphorescent to fluorescent dendrimers. Starting from PVCt330 that introduce oligocarbazole into the periphery of 4,4′-distyryl-1,1′-biphenylene (Figure 1), two dendrimers named PVAC2 and PVACA have been synthesized and investigated by gradually replacing carbazole with diphenylamine in the dendritic wedge. Attributed to the stronger electron-donating ability of diphenylamine than carbazole, the HOMO level is found to be increased following a sequence of PVCt3 (−5.35 eV) < PVAC2 (−5.20 eV) < PVACA (−4.95 eV). Compared with PVCt3, an improved nondoped device performance including brightness, luminous efficiency, and power efficiency is realized for PVAC2 and PVACA. Noticeably, PVACA achieves a turn-on voltage of 2.6 V which is even lower than the theoretical limit (2.78 V).
2. RESULTS AND DISCUSSION

2.1. Synthesis and Thermal Properties. The synthetic route for the fluorescent dendrimers PVAC2 and PVACA is presented in Scheme 1. First, a CuI-catalyzed Ullmann reaction between 4-(bis(4-iodophenyl)amino)benzaldehyde and the second-generation carbazole (D2) or carbazole/diphenylamine hybrid dendron (DA) was performed to afford the key intermediates MD1 and MD2. Then they were treated with 4,4-bis(di-ethylphosphonomethyl)biphenyl via a Horner–Wadsworth–Emmons reaction to give the desired dendrimers PVAC2 and PVACA in a yield of 65–71%. Their chemical structures are characterized by 1H NMR, matrix-assisted laser desorption/ionization-time of flight (MALDI-TOF) mass spectrometry (MS) and elemental analysis. They all show excellent solubility in common solvents, such as toluene, chlorobenzene, and tetrahydrofuran (THF) etc., assuring to form a good film via spin-coating.

Also, the thermal stabilities of PVAC2 and PVACA compared with PVCt3 were investigated by thermogravimetry analysis (TGA) and differential scanning calorimetry (DSC). They are thermally stable, showing 5% weight loss of 337, 519 and 542 °C for PVCt3, PVAC2, and PVACA, respectively (Figure 2). Moreover, the Tg is found to be down from 372 °C of PVCt3 to 342 °C of PVAC2 and 293 °C of PVACA. This can be ascribed to the weaker rigidity of diphenylamine relative to carbazole.

2.2. Photophysical Properties. The UV and photoluminescence (PL) spectra in toluene for PVCt3, PVAC2, and PVACA are shown in Figure 3a. It can be clearly seen that with the increasing number of diphenylamine, the 298 nm characteristic absorption from carbazole in PVCt3 and PVAC2 disappears, and a new absorption band centered at about 310 nm is observed in PVACA. Meanwhile, the low-energy band that is related to π−π* transitions of the core shows an obvious bathochromic shift from PVCt3 to PVAC2 and PVACA. Also the corresponding optical band gap is reduced from 3.02 to 2.79 and 2.78 eV (Table 1). Accordingly, the maximum emission has a red shift from 418 nm of PVCt3 to 446 nm of PVAC2 and 451 nm of PVACA. The solution PL quantum yield (PLQY) is determined to be 0.94, 0.85, and 0.54 for PVCt3, PVAC2, and PVACA using 9,10-diphenylanthracene as the standard, respectively. Unlike the rigid carbazole, the flexible diphenylamine moiety is easier to bring about nonradiative decay and thus lowered the PLQY. Ongoing from solution to films, the PL spectra become structureless accompanied by a red-shift of 20 nm (Figure 3b). The observation indicates the existence of aggregation in solid states to some degree, which is further proved by the decreased film PLQYs (0.39–0.59).

2.3. Electrochemical Properties. The electrochemical performance of the dendrimers was performed in dichloromethane using cyclic voltammetry (CV). The CV data are shown in Figure 4, during the anodic scan, they all exhibit multiple oxidation processes, whereas during the cathodic scan no reduction waves are detected. Because diphenylamine has a stronger electron-donating capability than carbazole, the first oxidation wave is reasonably downshifted toward a negative potential. Using ferrocene/ferrocenium as an internal standard (−4.8 eV), the HOMO level is accordingly enhanced from −5.35 eV of PVCt3 to −5.20 eV of PVAC2 and −4.95 eV of PVACA. The observed variation implies the favored hole injection and transporting, which is beneficial for the realization of low-voltage-driving solution-processed OLEDs.

Scheme 1. Synthetic Routes of PVAC2 and PVACA: (i) (+/−)-trans-1,2-Diaminocyclohexane, Cuprous Iodide, Tripotassium Phosphate, Toluene, 110 °C; (ii) Potassium tert-Butanolate, THF, 0 °C

Figure 1. Structure of PVCt3, PVAC2, and PVACA.
In addition, together with the absorption optical band gap, the lowest unoccupied molecular orbital (LUMO) level is estimated to be \(-2.33\), \(-2.43\), and \(-2.17\) eV for PVCt3, PVAC2, and PVACA, respectively.

### 2.4. Electroluminescence Properties

To explore the electroluminescence (EL) performances of the dendrimers, we fabricated the nondoped OLEDs with a structure of ITO/PEDOT:PSS/dendrimer/TPBI/LiF/Al (Figure 5a). Here the dendrimers of PVCt3, PVAC2, or PVACA without the usage of any additional host were independently used as the emitting layer, and 1,3,5-tris(1-phenyl-benzimidazol-2-yl)benzene (TPBI) as the hole-blocking and electron-transporting layer. Similar to the PL counterpart, the EL spectra exhibited a distinct red-shift from PVCt3 to PVAC2 and PVACA (Figure 5b), finding CIE values of (0.16, 0.10), (0.16, 0.23) and (0.18, 0.25), respectively.

Figure 5c,d presents the performances of the nondoped OLEDs, and the key data are summarized in Table 2. As shown, both the \(J-V\) and \(L-V\) curves move to a negative voltage from PVCt3 to PVAC2 and PVACA. Consequently, the turn-on voltage is significantly decreased from 3.6 to 3.2 and 2.6 V. The observation is in well agreement with their HOMO levels. On one hand, the growing HOMO can lower the hole injection barrier. On the other hand, due to the enhanced HOMO difference between PVACA and TPBI (Figure 5a), the injected holes may tend to accumulate on PVACA. Albeit its varied LUMO, electrons could still be injected from TPBI to PVACA easily via a Coulomb force, leading to the decreased driving voltage. It should be noted that the PVACA-based device displays a turn-on voltage that is even smaller than the theoretical limit (2.78 V). According to the literature,\(^3\) this may be ascribed to the thermally assisted EL process.

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**Table 1. Optical, Electrochemical, and Thermal Properties of PVCt3, PVAC2, and PVACA**

| dendrimer | \(\lambda_{\text{abs}}\) \[^{a}\] [nm] | \(\lambda_{\text{em}}\) \[^{s}\] [nm] | \(\Phi_{\text{PL}}\) \[^{b}\] | \(\lambda_{\text{em}}\) \[^{c}\] [nm] | \(\Phi_{\text{PL}}\) \[^{d}\] | \(E_{\text{g}}\) \[^{e}\] [eV] | HOMO/LUMO\[^{f}\] [eV] | \(T_{\text{d}}\) [°C] | \(T_{\text{g}}\) [°C] |
|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| PVCt3     | 298, 353        | 418, 444(s)     | 94              | 439(s), 452     | 59              | 3.02            | \(-5.35/-2.33\) | 537             | 372             |
| PVAC2     | 298, 335, 399   | 446, 470(s)     | 85              | 466, 483(s)     | 45              | 2.79            | \(-5.20/-2.41\) | 519             | 342             |
| PVACA     | 314, 396        | 451             | 54              | 469(s), 483     | 39              | 2.78            | \(-4.95/-2.17\) | 542             | 293             |

\[^{a}\] Measured in a solution of \(10^{-6}\) M. \[^{b}\] Measured in solution with a standard blue fluorophor 9,10-diphenylanthracene (\(\Phi_{\text{PL}} = 0.90\)). \[^{c}\] Measured in the neat film. \[^{d}\] Determined in the neat film using an integrating sphere. \[^{e}\] Determined from the absorption onset. \[^{f}\] HOMO = \(-e(E_{\text{ox}} + 4.8\) V), LUMO = HOMO + \(E_{\text{g}}\) where \(E_{\text{ox}}\) is the onset value of the first oxidation.
accelerate the development of solution-processible blue PVAC2 and PVACA. We believe that this strategy will successfully be achieved for the nondoped devices based on dendrimer PVCt3, the HOMO levels of PVAC2 and PVACA instead of oligocarbazole. Compared with the reference where the carbazole/diphenylamine hybrid dendron is adopted and PVACA have been newly synthesized and investigated, 4. EXPERIMENT

In conclusion, two blue fluorescent dendrimers named PVAC2 and PVACA reveal a much better device performance. For example, a peak brightness of 9667 and 6596 cd/m², a maximum luminous efficiency of 5.20 and 3.88 cd/A, and a peak power efficiency of 4.80 and 4.00 lm/W are attained for PVAC2 and PVACA, respectively. The observed inferior performance of PVACA to PVAC2 may originate from the reduced efficiency as a function of current density.

Table 2. Nondoped Device Performance of PVCt3, PVAC2, and PVACA

| device  | $V_{on}$ [V] | $I_{max}$ [cd m\(^{-2}\)] | $\eta_{max}$ [cd A\(^{-1}\)] | $\eta_{max}$ [lm W\(^{-1}\)] | EQE (%) | CIE ($x$, $y$) |
|---------|--------------|------------------------------|-------------------------------|-------------------------------|---------|---------------|
| PVCt3   | 3.6          | 4729                         | 2.89                          | 2.37                          | 2.81    | (0.16, 0.10)  |
| PVAC2   | 3.2          | 9667                         | 5.20                          | 4.80                          | 2.83    | (0.16, 0.23)  |
| PVACA   | 2.6          | 6596                         | 3.88                          | 4.00                          | 2.04    | (0.18, 0.25)  |

“Turn-on voltage at 1 cd m\(^{-2}\), “Maximum external efficiency. *CIE coordinates.

2.37 lm/W), PVAC2 and PVACA reveal a much better device performance. For example, a peak brightness of 9667 and 6596 cd/m², a maximum luminous efficiency of 5.20 and 3.88 cd/A, and a peak power efficiency of 4.80 and 4.00 lm/W are attained for PVAC2 and PVACA, respectively. The observed inferior performance of PVACA to PVAC2 may originate from the reduced film PLQY (0.39 for PVACA and 0.45 for PVAC2).

3. CONCLUSIONS

In conclusion, two blue fluorescent dendrimers named PVAC2 and PVACA have been newly synthesized and investigated, where the carbazole/diphenylamine hybrid dendron is adopted instead of oligocarbazole. Compared with the reference dendrimer PVCt3, the HOMO levels of PVAC2 and PVACA are enhanced to favor the hole injection. As a result, lower driving voltages and thus higher power efficiencies are enhanced to favor the hole injection. As a result, lower driving voltages and thus higher power efficiencies are successfully achieved for the nondoped devices based on PVAC2 and PVACA. We believe that this strategy will accelerate the development of solution-processible blue fluorescent dendrimers capable of being used for power-efficient OLEDs.

4. EXPERIMENT

4.1. General Information. The chemical structures were characterized by \(^1\)H NMR (Bruker AVANCE 400 NMR), MALDI-TOF MS (AXIMA CFR MS apparatus) and elemental analysis (C, N, H on a Bio-Rad elemental analysis system). TGA and DSC were tested under N₂ at a heating rate of 10 °C min\(^{-1}\) with TGA 7 and Elmer-DSC 7 systems which are obtained from PerkinElmer. The UV–vis absorption and PL spectra were recorded with a PerkinElmer Lambda 35 UV/vis spectrometer and LS 50B spectrophotometer. The thin solid films for measurement were obtained on quartz by spin-coating. The solution PLQYs were measured with a standard blue fluorophor 9,10-diphenylanthracene (Φ\(_{PL} = 0.90\)), and the solid film PLQYs were recorded by using an integrating sphere on a HAMAMATSU (C9920-02). CV experiments were operated on an electrochemical analyzer (CHI660a) with a glass carbon working electrode and a Pt counter electrode under a scan rate of 100 mV s\(^{-1}\) against an Ag/AgCl reference electrode with a solution of 0.1 M n-Bu₄NCIO₄ in dry dichloromethane as the electrolyte.

4.2. Device Fabrication and Measurement. ITO-coated patterned glass substrates were precleaned carefully and used ultraviolet ozone to treat the substrates of 30 min. Then, a PEDOT:PSS (Clevios P Al4083) film of 40 nm thickness was prepared on the top of ITO and baked for 45 min at 120 °C. Then the solutions of the dendrimers in chlorobenzene were spin-coated on PEDOT:PSS as the emissive layer (45 nm). Then the solutions of the dendrimers in chlorobenzene were spin-coated on PEDOT:PSS as the emissive layer (45 nm). After annealed at 100 °C (30 min) under N₂, the films were transferred into a evaporator, then at a pressure of less than 4.0 × 10\(^{-4}\) Pa a film of TPBI (55 nm) was deposited on the emissive layer. Finally, LiF (0.5 nm) and Al (100 nm) were deposited as the cathode. A PR650 spectra colorimeter was used to record the EL spectra and CIE values. The $J$–$V$–$L$ properties were obtained from a calibrated silicon photodiode and a Keithley 2400/2000 source meter. The external quantum efficiencies (EQEs) were calculated based on the current $J$–$V$–$L$ properties and the EL spectra assuming a Lambertian emission.

4.3. Synthetic. All commercially available reagents and chemicals were used without further purification. Solvents for chemical synthesis were purified as the standard procedures. D2,\(^{25}\) DA\(^{45}\) and 4-(bis(4-iodophenyl)amino)benzaldehyde\(^{33}\) were synthesized according to the reference method.

4.3.1. MDI. D2 (18.2 g, 25.2 mmol), 4-(bis(4-iodophenyl)amino)benzaldehyde (6.3 g, 12.0 mmol), CuI (0.5 g, 2.4 mmol) and K₂PO₄ (10.2 g, 48.0 mmol) were mixed in a flask. Toluene (150 mL) and (+/-)-trans-1,2-diaminocyclohexane
(0.6 mL, 4.8 mmol) were added under argon, then the reaction solution was heated to reflux at 110 °C for 24 h under vigorous stirring. After the reaction system cooled, H₂O and CH₂Cl₂ were extracted to get the crude product. The organic was purified by column chromatography using a CH₂Cl₂/n-hexane (1:3) eluent to afford a white solid MD1 (13.0 g, 60%). ¹H NMR (400 MHz, CDCl₃): δ 9.99 (s, 1H), 8.25 (d, J = 27.6 Hz, 13H), 7.94 (d, J = 8.5 Hz, 2H), 7.83 (d, J = 8.6 Hz, 4H), 7.78 (d, J = 8.7 Hz, 5H), 7.67 (t, J = 9.1 Hz, 9H), 7.48 (t, J = 8.1 Hz, 10H), 7.40 (t, J = 9.4 Hz, 10H). 1.45 (s, 12H).

4.3.2. MD2. Compound MD2 was prepared similar to MD1 in a yield of 85% by starting with DA instead of D₂. ¹H NMR (400 MHz, CDCl₃): δ 10.23 (s, 1H), 7.75 (d, J = 8.4 Hz, 8H), 7.71−7.61 (m, 8H), 7.60 (d, J = 8.3 Hz, 4H), 7.38 (d, J = 8.7 Hz, 4H), 7.23 (d, J = 2.1 Hz, 2H), 7.24−7.15 (m, 10H), 7.07 (dd, J = 11.6, 7.9 Hz, 10H), 6.96−6.84 (m, 8H), 6.77 (d, J = 7.5 Hz, 6H), 2.23 (s, 12H).

4.3.3. PVAC2. A dry THF (50 mL) solution of 4,4'-bis(diethylphosphonomethyl)biphenyl (0.6 g, 1.4 mmol) and MD1 (5.2 g, 3.0 mmol) was cooled to 0 °C under argon. Then the t-BuOK (1.6 g, 14.0 mmol) solution in THF (20 mL) was added under vigorous stirring. After stirring 8 h at 30 °C, H₂O and CH₂Cl₂ were extracted to get the crude product. The product was purified by column chromatography with a CH₂Cl₂/n-hexane (1:6) eluent to afford a solid PVAC2 (3.5 g, 71%). ¹H NMR (400 MHz, CDCl₃): δ 8.26 (d, J = 1.7 Hz, 8H), 8.17 (d, J = 1.5 Hz, 16H), 7.73 (d, J = 8.7 Hz, 8H), 7.70 (d, J = 8.8 Hz, 8H), 7.66 (d, J = 1.6 Hz, 6H), 7.65−7.59 (m, 14H), 7.57 (d, J = 8.7 Hz, 8H), 7.46 (dd, J = 8.7, 1.7 Hz, 16H), 7.40 (d, J = 8.4 Hz, 4H), 7.35 (d, J = 8.6 Hz, 16H), 7.18 (d, J = 6.6 Hz, 4H), 1.45 (d, J = 14.4 Hz, 144H). MALDI-TOF MS: 3573.9 [(M + 1)+]. Anal. Calcd for C₁₇₀H₁₄₃N₁₄: C, 87.40; N, 7.40; H, 5.67. Found: C, 87.40; N, 6.69; H, 5.61. Found: C, 87.44; N, 6.86; H, 5.68.

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Notes
The authors declare no competing financial interest.

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(20) Wang, Y.; Wang, S.; Shao, S.; Ding, J.; Wang, L.; Jing, X.; Wang, F. Synthesis and properties of greenish-blue-emitting iridium dendrimers with N-phenylcarbazole-based polyether dendrons by a post-dendronization route. *Dalton Trans.* 2015, 44, 1052–1059.

(21) Markham, J. P. J.; Lo, S.-C.; Magennis, S. W.; Burn, P. L.; Samuel, I. D. W. High-efficiency green phosphorescence from spin-coated single-layer dendrimer light-emitting diodes. *Appl. Phys. Lett.* 2002, 80, 2645–2647.

(22) Wang, Y.; Wang, S.; Zhao, N.; Gao, B.; Shao, S.; Ding, J.; Wang, L.; Jing, X.; Wang, F. Facile synthesis of self-host functional iridium dendrimers up to the fourth generation with N-phenylcarbazole-based polyether dendrons for non-doped phosphorescent organic light-emitting diodes. *Polym. Chem.* 2015, 6, 1180–1191.

(23) Wang, Y.; Wang, S.; Ding, J.; Wang, L. Multinuclear Iridium Complex Encapsulated by Oligocarbazole Dendrons for Enhanced Nondoped Device Efficiency. *ACS Omega* 2018, 3, 15308–15314.

(24) Zhu, M.; Zou, J.; He, X.; Yang, C.; Wu, H.; Zhong, C.; Qin, J.; Cao, Y. Triphenylamine Dendronized Iridium(III) Complexes: Robust Synthesis, Highly Efficient Nondoped Orange Electrophosphorescence and the Structure-Property Relationship. *Chem. Mater.* 2012, 24, 174–180.

(25) Ding, J.; Liu, J.; Cheng, Y.; Xie, Z.; Wang, L.; Jing, X.; Wang, F. Solution-Processible Red Iridium Dendrimers based on Oligocarbazole Host Dendrons: Synthesis, Properties, and their Applications in Organic Light-Emitting Diodes. *Adv. Funct. Mater.* 2008, 18, 2754–2762.

(26) Chen, L.; Wang, S.; Yan, Z.; Ding, J.; Wang, L. An oligocarbazole-encapsulated heteroleptic red iridium complex for solution-processed nondoped phosphorescent organic light-emitting diodes with over 10% external quantum efficiency. *J. Mater. Chem. C* 2017, 5, 5749–5756.

(27) Zhao, L.; Wang, S.; Liu, J.; Ding, J.; Wang, L. Solution processable red iridium dendrimers containing oligocarbazole dendrons for efficient nondoped and doped phosphorescent OLEDs. *J. Mater. Chem. C* 2017, 5, 9753–9760.

(28) Sasabe, H.; Toyota, N.; Nakanishi, H.; Ishizaka, T.; Pu, Y.-J.; Kido, J. 3,3’-Bicarbazole-Based Host Materials for High-Efficiency Blue Phosphorescent OLEDs with Extremely Low Driving Voltage. *Adv. Mater.* 2012, 24, 3212–3217.

(29) Wang, Y.; Wang, S.; Ding, J.; Wang, L.; Jing, X.; Wang, F. Dendron engineering in self-host blue iridium dendrimers towards low-voltage-driving and power-efficient nondoped electrophosphorescent devices. *Chem. Commun.* 2017, 53, 180–183.

(30) Zhao, L.; Wang, S.; Ding, J.; Wang, L. Solution processible distyrylarylene-based fluorescent dendrimers: Tuning of carbazole-dendron generation leads to nondoped deep-blue electroluminescence. *Org. Electron.* 2018, 53, 43–49.

(31) Sasabe, H.; Nakanishi, H.; Watanabe, Y.; Yano, S.; Hirasawa, M.; Pu, Y.-J.; Kido, J. Extremely Low Operating Voltage Green Phosphorescent Organic Light-Emitting Devices. *Adv. Funct. Mater.* 2013, 23, 5550–5555.

(32) Kundu, P.; Justin Thomas, K. R.; Lin, J. T.; Tao, Y.-T.; Chien, C.-H. High-Tg carbazole derivatives as blue-emitting hole-transporting materials for electroluminescent devices. *Adv. Funct. Mater.* 2003, 13, 445–452.

(33) Xia, H.; He, J.; Peng, P.; Zhou, Y.; Li, Y.; Tian, W. Synthesis and photophysical properties of triphenylamine-based dendrimers with 1,3,5-triphenylbenzene cores. *Tetrahedron Lett.* 2007, 48, 5877–5881.