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Synthesis of carbazole-based dendrimer: host material for highly efficient solution-processed blue organic electrophosphorescent diodes

Wei Jiang^a, Jinan Tang^a, Wen Yang^a, Xinxin Ban^a, Bin Huang^a, Yunqian Dai^a, Yueming Sun^{a,*}, Lian Duan^{b,*}, Juan Qiao^b, Liduo Wang^b, Yong Qiu^b

^a School of Chemistry and Chemical Engineering, Southeast University, Nanjing, Jiangsu 211189, PR China ^b Department of Chemistry, Tsinghua University, Beijing 100084, PR China

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ABSTRACT

This paper reports the synthesis and physical properties of two novel carbazole-based dendritic host materials Cz-CCP and Cz-mCP for solution-processed blue phosphorescent organic light-emitting devices (PhOLEDs). These dendritic hosts exhibit high triplet energy (\geq 2.85 eV), excellent film-forming ability (with low root-mean-square (rms) values less than 0.2 nm), high glass-transition temperatures in the range of 242–248 °C, and the appropriate HOMO energy levels (-5.33--5.35 eV) facilitating the transfer of holes from Poly(3,4-ethylenedioxythiophene):Poly(styrene-4-sulfonate) (PEDOT:PSS) to the emitting layer. The single-layer device using Cz-CCP and Cz-mCP as the host for the phosphorescence emitter iridium(III) bis(4,6-difluorophenylpyridinato)-picolinate (FIrpic) showed the maximum luminance efficiencies of 9.6 and 10.8 cd A⁻¹, respectively. By introducing a thin 1,3,5-tris(1-phenyl-1H-benzo[d] imidazol-2-yl)benzene (TPBI) electron-transporting and exciton-confining layer, the maximum efficiency of the solution-processed double-layer device based on Cz-CCP and Cz-mCP can be further improved to 20.5 and 22.7 cd A⁻¹, and maximum external quantum efficiencies as high as 10.2% and 11.5%, respectively. These results demonstrated that the newly synthesized, carbazole-based dendritic host materials are advantageous for fabrication of highly efficient blue PhOLEDs.

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1. Introduction

Phosphorescent organic light-emitting diodes (PhOLEDs) have attracted considerable attention due to their promising applications in highly energy-efficient flat-panel displays, and being potential candidates for the next generation of lighting sources.^{1–5} To minimize the triplet—triplet annihilation and concentration quenching effects, the triplet emitters have to be well dispersed into a host matrix at a relatively low concentration. Therefore, the development of efficient host materials is of great importance to achieve the high performance PhOLEDs. Currently, the design of suitable host materials for the efficient and stable blue PhOLEDs still remains a challenge due to the requirement of high triplet energy (>2.75 eV, to confine the electro-generated triplet excitons on the dopant molecules),^{6,7} while the search of host for the green and red triplet emitters is relatively easier because of their low triplet energy levels.

Recently, solution-processed PhOLEDs are highly desirable to simplify the fabrication process and achieve the cheaper and largerarea displays.^{8–15} Even though polymer-based host materials allow easy access to the solution-processing strategy, the impurities in polymer host materials could result in exciton quenching and the device failure. Compared with polymers, conjugated dendrimers are believed to have a number of advantages including excellent solubility, facilitated formation of good quality film, well-defined structures, and high degree of purity.^{6,16–22} These unique features render this kind of dendritic materials rather promising in using as host material for solution-processed PhOLEDs.

Carbazole-based molecules have been widely used as host materials for blue PhOLEDs due to their high triplet energy and excellent hole-transporting properties.^{23–30} In this paper, we proposed to modify 1,4-bis(9-carbazolyl)benzene (CCP) and 1,3bis(9-carbazolyl)benzene (mCP) by linking of two carbazole moieties into the 3, 6 positions of the carbazole units to build novel dendritic host materials. The novel dendrimers are Cz-CCP and CzmCP, which possess the following distinct characteristics: (i) the high triplet energy levels (2.85 eV); (ii) the appropriate HOMO energy levels (-5.33--5.35 eV); (iii) the capability of forming stable amorphous thin films. Additionally, the introduction of the *tert*-butyl groups ensures the good solubility of our novel dendrimers in common solvents. As a result, the solution-processed devices based those new hosts show excellent performances, with



^{*} Corresponding authors. Tel./fax: +86 25 52090621; e-mail addresses: 101011462@seu.edu.cn (Y. Sun), duanl@tsinghua.edu.cn (L. Duan).

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the luminous efficiency (LE) of 22.7 cd A^{-1} and the external quantum efficiency (EQE) of 11.5% for blue PhOLEDs. These promoted efficiencies of the devices, which are outstanding with respect to other works related to the solution-processed blue PhOLEDs based on dendritic hosts.

2. Experimental

2.1. General information

All reactants and solvents, unless otherwise stated, were purchased from commercial sources and used as received. ¹H NMR and ¹³C HMR spectra were measured on a Bruker ARX300 NMR spectrometer with tetramethylsilane as the internal standard. Elemental analysis was performed on an Elementar Vario EL CHN elemental analyzer. Mass spectrometry was performed with a Thermo Electron Corporation Finnigan LTQ mass spectrometer. Absorption spectra were recorded with a UV–vis spectrophotometer (Agilent 8453) and PL spectra were recorded with a fluorospectrophotometer (Jobin Yvon, FluoroMax-3). TGA was recorded with a Netzsch simultaneous thermal analyzer (STA) system (STA 409PC) under a dry nitrogen gas flow at a heating rate of 10 °C min⁻¹. Glass-transition temperature was recorded by DSC at a heating rate of 10 °C min⁻¹ with a thermal analysis instrument (DSC 2910 modulated calorimeter). Cyclic voltammetry was 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. The film surface morphology was recorded by AFM (Seiko Instruments, SPA-400).

2.2. Device fabrication and performance measurements

In a general procedure, indium-tin oxide (ITO)-coated glass substrates were pre-cleaned carefully and treated by UV ozone for 4 min. An aqueous solution of Poly(3,4-ethylenedioxythiophene) and Poly(styrene-4-sulfonate)(PEDOT:PSS) was spin-coated onto the ITO substrate and the layer thickness was carefully controlled at 40 nm. After being baked at 210 °C for 10 min, the substrate was then transferred into a nitrogen glove box. Then a FIrpic-doped host: 1,3-bis[4-*tert*-butylphenyl0-1,3,4-oxidiazolyl]phenyl-ene (OXD-7) layer was spin-coated onto the PEDOT:PSS layer from 1,2-dichloroethane solution and annealed at 100 °C for 30 min. Finally, the substrate was transferred into an evaporation chamber, where the TPBI was evaporated at an evaporation rate of 1-2 Å/s under a pressure of 4×10^{-4} Pa and the Cs₂CO₃/Al bilayer cathode



Scheme 1. Synthetic routes toward Cz-CCP and Cz-mCP.



Fig. 1. Normalized UV-vis absorption (Abs, red curve), photoluminescence (PL, blue curve) and phosphorescence (77 K) (PH, green curve) spectra of (a) Cz-CCP and (b) Cz-mCP.



Fig. 2. (a) TGA traces of Cz-CCP and Cz-mCP recorded at a heating rate of 10 °C min⁻¹, (b) DSC measurement recorded at a heating rate of 10 °C min⁻¹.

was evaporated at evaporation rates of 0.2 and 10 Å/s for Cs₂CO₃ and Al, respectively, under a pressure of 1×10^{-3} Pa. The current-voltagebrightness characteristics of the devices 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.

2.3. Quantum chemical calculations

The geometrical and electronic properties of Cz-CCP and Cz-mCP were calculated with 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.³¹

2.4. Materials

Compounds 3,6-diiodo-9-(toluene-4-sulfonyl)carbazole³² and 3,6-bis(3,6-di-*tert*-butyl-carbazol-9-yl)-carbazole³³ were prepared according to published procedures. Cz-CCP and Cz-mCP were synthesized by the same procedure.

2.4.1. Synthesis of Cz-CCP. 1,4-Dibromobenzene (5.0 mmol), 3,6bis(3,6-di-tert-butyl-carbazol-9-yl)-carbazole (12.0 mmol), copper(I) iodide (0.25 mmol), 18-crown-6 (0.25 mmol) and K₂CO₃ (20.0 mmol) were added to 10 mL of DMPU solution. The mixture was heated to 180 °C under nitrogen for 36 h. After the reaction finished, the reaction mixture was extracted with dichloromethane and water. The organic layer was dried by anhydrous MgSO₄ and filtered. The product was isolated by silica gel column chromatography using petroleum ether/ethyl acetate (20:1) eluent to afford a white solid (2.67 g, 35.2%). ¹H NMR (300 MHz, CDCl₃, δ): 8.31 (s, 4H), 8.18 (s, 8H), 8.13 (d, J=3.4 Hz, 4H), 7.87 (d, J=8.6 Hz, 4H), 7.72 (d, J=8.6 Hz, 4H), 7.50 (d, J=8.4 Hz, 8H), 7.42 (d, J=8.6 Hz, 8H), 1.49 (s. 72H). ¹³C NMR (300 MHz, CDCl₃, δ): 142.7, 140.2, 140.1, 136.9, 131.4. 130.8. 128.8. 128.7. 126.2. 124.3. 123.6. 123.2. 119.5. 116.3. 111.1. 109.1. 32.0. 31.8. MS (MALDI-TOF) [m/z]: calcd for C₁₁₀H₁₁₂N₆. 1518.1; found, 1518.5. Anal. Calcd for C110H112N6 (%): C, 87.03; H, 7.44; N 5.54. Found: C, 87.10; H, 7.40; N 5.45.

2.4.2. Synthesis of Cz-mCP. 1,3-Dibromobenzene (5.0 mmol), 3,6-bis(3,6-di-tert-butyl-carbazol-9-yl)-carbazole (12.0 mmol), copper(I) iodide (0.25 mmol), 18-crown-6 (0.25 mmol) and K_2CO_3



Fig. 3. AFM topographic images of Cz-CCP, Cz-mCP, and mCP doped with 10 wt % Firpic. The films were prepared through spin-coating from 1,2-dichloroethane solutions onto ITO/ PEDOT:PSS.



Fig. 4. Oxidation part of the CV curves of Cz-CCP and Cz-mCP in CH_2Cl_2 solutions $(10^{-3}\mbox{ M}).$

(20.0 mmol) were added to 10 mL of DMPU solution. The mixture was heated to 180 °C under nitrogen for 36 h. After the reaction finished, the reaction mixture was extracted with dichloromethane and water. The organic layer was dried by anhydrous MgSO₄ and filtered. The product was isolated by silica gel column chromatography using petroleum ether/ethyl acetate (20:1) eluent to afford a white solid (3.04 g, 40.1%). ¹H NMR (300 MHz, CDCl₃, δ): 8.30 (s, 4H), 8.17 (s, 8H), 8.12–8.15 (m, 2H), 7.99 (d, *J*=7.6 Hz, 2H), 7.84 (d, *J*=8.5 Hz, 4H), 7.71 (d, *J*=8.6 Hz, 4H), 7.47 (d, *J*=8.4 Hz, 8H), 7.37 (d, *J*=8.6 Hz, 8H), 1.48 (s, 72H). ¹³C NMR (300 MHz, CDCl₃, δ): 142.7, 140.2, 140.1, 139.3, 132.0, 126.6, 126.2, 125.7, 124.4, 123.9, 123.7, 122.9, 120.2, 119.8,

116.4, 111.0, 109.6, 109.1, 32.0, 31.8. MS (MALDI-TOF) [m/z]: calcd for C₁₁₀H₁₁₂N₆, 1518.1; found, 1518.4. Anal. Calcd for C₁₁₀H₁₁₂N₆ (%): C, 87.03; H, 7.44; N 5.54. Found: C, 87.18; H, 7.39; N 5.35.

3. Results and discussion

The dendrimers Cz-CCP and Cz-mCP were synthesized via a classic Ullmann reaction, as illustrated in Scheme 1. Firstly, the key intermediate 3,6-bis(3,6-di-tert-butyl-carbazol-9-yl)-carbazole (3) was prepared via a three-step reaction with a total yield of 40%. Secondly, the aromatic C–N coupling reactions of 1,4dibromobenzene and 1,3-dibromobenzene with 3 led to Cz-CCP and Cz-mCP with a yields of 35.2% and 40.1%, respectively. Finally, all dendrimers were purified by the silica column method and recrystallization, yielding very pure white powders. ¹H NMR, ¹³C NMR, matrix-assisted laser desorption ionization time-of-flight (MALDI-TOF) mass spectrometry, and elemental analysis were employed to confirm the chemical structures of above-mentioned dendrimers as described in experimental section. Fig. 1 depicts the UV-vis absorption and photoluminescence (PL) spectra of Cz-CCP and Cz-mCP in CH₂Cl₂. Both the absorption and the PL spectra of Cz-CCP are very similar to those of Cz-mCP. Three major absorption peaks locate at 240, 297, 348 nm in the absorption spectra, while the emission peaks appear at 402 nm in the PL spectra. The phosphorescence spectra measured from a frozen 2-methyltetrahydrofuran matrix at 77 K are also shown in Fig. 1. The triplet energies of the Cz-CCP and Cz-mCP were determined to the same values of 2.85 eV by the highest energy 0-0 phosphorescent emission, which are sufficiency high to serve as the appropriate hosts for FIrpic.

The thermal stabilities of the dendrimers were investigated by thermal gravimetric analyses (TGA) and differential scanning calorimetry (DSC) under nitrogen atmosphere (see Fig. 2). Cz-CCP and Cz-mCP have outstanding thermal stabilities with the



Fig. 5. Optimized geometries and calculated HOMO and LUMO density maps for CCP, mCP, Cz-CCP, and Cz-mCP according to DFT calculations at B3LYP/6-31* level.

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Device performances of the electrophosphorescent OLEDs

Device	Host	$V_{\rm on} [V]^{\rm a}$	B _{max} [cd m ⁻²] ^b	$\eta_{c,max}$ [cd A ⁻¹] ^c	$\eta_{\mathrm{ext,max}}$ [%] ^d	CIE (<i>x</i> , <i>y</i>)
A	Cz-CCP	4.3	19,500	9.6	4.8	(0.16, 0.32)
	Cz-mCP	4.4	21,000	10.8	5.6	(0.16, 0.32)
В	Cz-CCP	4.6	26,500	20.5	10.2	(0.15, 0.34)
	Cz-mCP	4.6	27,300	22.7	11.5	(0.15, 0.33)

^a Recorded at 1 cd m^{-2} .

^b Maximum luminance.

^c Maximum current efficiency.

^d Maximum external quantum efficiency.

decomposition temperature of 415 °C and 443 °C, respectively. It is worth to noting that there are only weak endothermic steptransitions around 242 °C and 248 °C (the glass phase transition), for Cz-CCP and Cz-mCP, respectively. No noticeable signals related to the crystallization or melting is observed in the DSC curves. The excellent stability of glass phases were confirmed by the presence of endothermic step-transitions even after the samples were repeatedly heated and cooled. The high glass-transition temperature values of Cz-CCP and Cz-mCP is considered to benefit the good stability of the film morphology. As shown in Fig. 3, the surface of dendrimers doped with 10 wt % FIrpic are free of pinholes and are quite smooth, with the root-mean-square (rms) values less than 0.2 nm, while the films prepared from mCP doped with FIrpic exhibited more aggregation, or phase segregation, with the rms values larger than 1.0 nm. The above results clearly demonstrate that those dendrimers are capable of forming amorphous defectfree films through solution processing, as well as being the stable host of the homogeneously dispersed triplet emitters.

The highest occupied molecular orbital (HOMO) energy levels of Cz-CCP and Cz-mCP were characterized by the electrochemical cyclic voltammetry (CV) (Fig. 4). During the anodic scan in

dichloromethane. Cz-CCP and Cz-mCP exhibited similar reversible oxidation process, which can be assigned to the oxidation of electron-donating carbazole moiety, with the onset potentials of 1.12 and 1.14 V, respectively. No reduction waves were detected. On the basis of the onset potentials for oxidation, the HOMO energy of Cz-CCP and Cz-mCP were estimated to be -5.33 and -5.35 eV. respectively.³⁴ Compared with mCP (HOMO=-6.15 eV),³⁵ the HOMO energy levels of Cz-CCP and Cz-mCP have been well tuned to approach the work function of PEDOT (-5.2 eV), which allows in a low barrier of hole injection. DFT calculations were performed to understand the physical properties of the dendrimers at the molecular level. As shown in Fig. 5, the outer layer carbazole units are significantly twisted with inner carbazole unit, resulting in a nonplanar structure in each molecule. These geometrical characteristics can effectively prevent intermolecular interactions between π 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 and keeps the triplet energy gap at a high level of these dendrimers. The LUMO levels of the dendrimers are localized predominantly on the CCP and mCP core units, respectively, while the HOMO levels are distributed over the outer layer two carbazole fragments. Compared with CCP and mCP, the electron density of the inner-layer carbazole decreases when the generation increases due to the influence of the inductive electron-withdrawing effect of the outer layer carbazoles. Therefore, the HOMO level has increased as the increasing of the generation of the carbazole with the calculated values of -5.16 eV and -5.17 eV, which is in good agreement with the values measured by electrochemical CV.

The single-layer blue electrophosphorescent devices A with Cz-CCP and Cz-mCP as the host and FIrpic as the dopant with the configuration of ITO/PEDOT:PSS/Hosts:OXD-7(30 wt %):FIrpic(10 wt %)/ Cs₂CO₃/Al have been fabricated by spin-coating. The electrontransporting material OXD-7 was mixed into host materials to



Fig. 6. (a) Current–voltage (b) luminance–voltage characteristics and (c) luminance efficiency versus current density plots of the devices (d) the normalized EL spectra of devices at a driving voltage of 8 V.

facilitate the electron transport in the light-emitting laver.³⁶ As shown in Table 1, the electroluminescence (EL) spectra of Cz-CCP and Cz-mCP based devices are identical with the CIE coordinates of (0.16, 0.32), corresponding to the emission of FIrpic, and indicate the efficient energy transfer from hosts to FIrpic. The *I*–*V* characteristic curves of the device A demonstrate the turn-on voltages are only 4.3 V (for Cz-CCP) and 4.4 V (for Cz-mCP). These voltages are much lower than the values of the device based on simple carbazole derivative mCP or other previously reported data of solution-processed blue electrophosphorescent devices.^{7,9,10} The low turn-on voltages of Cz-CCP and Cz-mCP based devices are most likely due to their high-lying HOMO energy levels, which better matched better with the HOMO energy level of PEDOT:PSS, thereby facilitated holes injection of the device. As revealed in Fig. 6, the maximum LE values of these single-layer blue-emitting devices were 9.6 and 10.8 cd A⁻¹, and the corresponding EQE were 4.8 and 5.6%, respectively. To further improve the performance of the device, a thin TPBI electrontransporting and exciton-confining layer was inserted between the light-emitting layer and the cathode.^{37,38} Devices B with configurations of ITO/PEDOT:PSS/Hosts:OXD-7(30 wt %):FIrpic(10 wt %)/ TPBI/Cs₂CO₃/Al have also been fabricated. After the insertion of the TPBI layer, the maximum LE values of the Cz-CCP and Cz-mCP based devices were significantly promoted to 20.5 and 22.7 cd A^{-1} , and the corresponding maximum EQE were accordingly improved up to 10.2% and 11.5%, respectively. The properties of these devices are superior to the EL properties of mCP with the maximum LE values of 1.0 and 6.1 cd A⁻¹ for devices A and B, respectively.⁷ The promoted performance is probably due to the high glass-transition temperature of those dendritic hosts, which significantly enhance the capability of forming stable amorphous thin films. In addition, the lower barrier injection of holes from the PEDOT to the emitting layer may also contribute to the high performance of the devices.

4. Conclusions

In summary, we have designed and synthesized a novel series of solution-processable dendritic host materials Cz-CCP and Cz-mCP. Utilizing those dendrimers as host materials, highly efficient solution-processed blue PhOLEDs have been achieved in terms of the high triplet energy levels, high glass-transition temperatures and high-lying HOMO energy levels. The synthetic strategy presented herein should be extendable to other well-designed dendritic host materials for solution-processed PhOLEDs.

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References and notes

- 1. Tang, C. W.; Vanslyke, S. A. Appl. Phys. Lett. 1987, 51, 913.
- 2. Forrest, S. R. Nature 2004, 428, 911.
- Wu, C. C.; Lin, Y. T.; Wong, K. T.; Chen, R. T.; Chien, Y. Y. Adv. Mater. (Weinheim, Ger.) 2004, 16, 61.
- 4. Heeger, A. J. Angew. Chem., Int. Ed. 2001, 40, 2591.
- 5. Reineke, S.; Lindner, F.; Schwartz, G.; Seidler, N.; Walzer, K.; Lüeesem, B.; Leo, K. *Nature* **2009**, 459, 234.
- Holmes, R. J.; Forrest, S. R.; Tung, Y. J.; Kwong, R. C.; Brown, J. J.; Garon, S.; Thompson, M. E. Appl., Phys. Lett. 2003, 82, 2422.
- Ding, J.; Zhang, B.; LÜ,, J.; Xie, Z.; Wang, L.; Jing, X.; Wang, F. Adv. Mater. (Weinheim, Ger.) 2009, 21, 4983.
- Ge, Z. Y.; Hayakawa, T.; Ando, S.; Ueda, M.; Akiike, T.; Miyamoto, H.; Kajita, T.; Kakimoto, M. A. Adv. Funct. Mater. 2008, 18, 584.
- 9. Hou, L. D.; Duan, L.; Qiao, J.; Li, W.; Zhang, D. Q.; Qiu, Y. Appl. Phys. Lett. **2008**, 92, 263301.
- Jiang, W.; Duan, L; Qiao, J.; Wang, L. D.; Zhang, D. Q.; Qiu, Y. J. Mater. Chem. 2010, 20, 6131.
- 11. Jiang, W.; Duan, L.; Qiao, J.; Wang, L. D.; Zhang, D. Q.; Qiu, Y. J. Mater. Chem. **2011**, 21, 4918.
- Pandya, S. U.; Attar, H. A. A.; Jankus, V.; Zheng, Y.; Bryce, M. B.; Monkman, A. P. J. Mater. Chem. 2011, 21, 18439.
- 13. Tao, Y.; Yang, C.; Qin, J. Chem. Soc. Rev. 2011, 40, 2943.
- Ye, S.; Liu, Y.; Chen, J.; Lu, K.; Wu, W.; Du, C.; Liu, Y.; Wu, T.; Shuai, Z.; Yu, G. Adv. Mater. (Weinheim, Ger.) 2010, 22, 4167.
- Chien, C. H.; Kung, L. R.; Wu, C. H.; Shu, C. F.; Chang, S. Y.; Chi, Y. J. Mater. Chem. 2008, 18, 3461.
- Wang, L.; Jiang, Y.; Luo, J.; Zhou, Y.; Zhou, J.; Wang, J.; Pei, J.; Cao, Y. Adv. Mater. (Weinheim, Ger.) 2009, 21, 4854.
- 17. Jiang, Z.; Ye, T.; Yang, C.; Yang, D.; Zhu, M.; Zhang, C.; Qin, J.; Ma, D. *Chem. Mater.* **2011**, *23*, 771.
- 18. Burn, P. L.; Lo, S. C.; Samuel, I. D. W. Adv. Mater. (Weinheim, Ger.) 2007, 19, 1675.
- 19. Gupta, U.; Agashe, H. B.; Asthana, A.; Jain, N. K. Biomacromolecules **2006**, 7, 649.
- Lo, S. C.; Harding, R. E.; Brightman, E.; Burn, P. L.; Samuel, I. D. W. *J. Mater. Chem.* 2009, *19*, 3213.
 Rupert, B. L.; Mitchell, W. I.; Ferguson, A. I.; Kose, M. E.; Rance, W. L.; Rumbles.
- Rupert, B. L.; Mitchell, W. J.; Ferguson, A. J.; Kose, M. E.; Rance, W. L.; Rumbles, G.; Ginley, D. S.; Shaheen, S. E.; Kopidakis, N. J. Mater. Chem. 2009, 19, 5311.
- Lo, S. C.; Harding, R. E.; Shipley, C. P.; Stevenson, S. G.; Burn, P. L.; Samuel, I. D. W. J. Am. Chem. Soc. 2009, 131, 16681.
- Tsai, M. H.; Lin, H. W.; Su, H. C.; Ke, T. H.; Wu, C. C.; Fang, F. C.; Liao, Y. L.; Wong, K. T.; Wu, C. I. Adv. Mater. (Weinheim, Ger.) 2006, 18, 1216.
- 24. Sasabe, H.; Pu, Y. J.; Nakayama, K.; Kido, J. Chem. Commun. 2009, 6655.
- Jeon, S. O.; Yook, K. S.; Joo, C. W.; Lee, J. Y. Adv. Mater. (Weinheim, Ger.) 2011, 22, 1872.
- 26. Jiang, W.; Duan, L.; Qiao, J.; Wang, L. D.; Qiu, Y. Org. Lett. 2011, 13, 3146.
- 27. Chou, H. H.; Cheng, C. H. Adv. Mater. (Weinheim, Ger.) 2010, 22, 2468.
- Tao, Y.; Wang, Q.; Yang, C.; Wang, Q.; Zhang, Z.; Zou, T.; Qin, J.; Ma, D. Angew. Chem., Int. Ed. 2008, 47, 8104.
- Chang, H. H.; Tsai, W. S.; Chang, C. P.; Chen, N. P.; Wong, K. T.; Hung, W. Y.; Chen, S. W. Org. Electron. 2011, 12, 2025.
- 30. Seo, C. W.; Lee, J. Y. Org. Electron. 2011, 12, 1459.
- 31. Gaussian 03 (Revision B.05); Gaussian: Wallingford CT, 2004.
- 32. Tucker, S. H. J. Chem. Soc. 1926, 546.
- 33. McClenaghan, N. D.; Dehaen, W. J. Am. Chem. Soc. 2003, 123, 5356.
- Pommerehne, J.; Vesweber, H.; Guess, W.; Mahrt, R. F.; Bassler, H.; Porsch, M.; Daub, J. Adv. Mater. (Weinheim, Ger.) 1995, 7, 551.
- Wu, M. F.; Yeh, S. J.; Chen, C. T.; Murayama, H.; Tsuboi, T.; Li, W. S.; Chao, I.; Liu, S. W.; Wang, J. K. Adv. Funct. Mater. 2007, 17, 1887.
- Nakamura, A.; Tada, T.; Mizukami, M.; Yagyua, S. *Appl. Phys. Lett.* **2004**, *84*, 130.
 Plummer, E. A.; vin Dijken, A.; Hofstraat, H. W.; Cola, L. D.; Brunner, K. *Adv. Funct. Mater.* **2005**, *15*, 281.
- 38. Vaeth, K. M.; Tang, C. W. J. Appl. Phys. 2002, 92, 3447.