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Synthesis and properties of blue-light-emitting anthracene derivative with diphenylamino-fluorene

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1. Introduction

ABSTRACT

9,10-Bis-(9',9'-diethyl-7'-diphenylamino-fluoren-2-yl)-anthracene was synthesized from 9.10-anthracene diboronic acid and (7-bromo-9,9-diethyl-fluoren-2-yl)-diphenyl-amine in a Suzuki coupling reaction. A theoretical calculation of the three-dimensional structure suggests that it has a non-coplanar structure and inhibited intermolecular interactions. Upon excitation, the photoluminescence maximum of 9,10-bis-(9',9'-diethyl-7'-diphenylamino-fluoren-2-yl)-anthracene in solution and film were at 454 nm (solution) and 462 nm (film). The full width at half maximum of 9,10-bis-(9',9'-diethyl-7'-diphenylamino-fluoren-2-yl)-anthracene is 54 nm regardless of whether it is in a solution or a solid state. A multi-layered device using 9,10-bis-(9',9'-diethyl-7'-diphenylamino-fluoren-2-yl)-anthracene as emitting material exhibits maximum quantum efficiency of 3.3% (power efficiency of 2.1 lm/W, current efficiency of 4.17 cd/A) and a blue Commission Internationale de l'Eclairage chromaticity coordinates (x = 0.14, y = 0.17).

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systems having all the attributes of high EL efficiency, a long operational lifetime, and deep-blue color, are rare [3–15].

The advantages of anthracene are easy substitution at the 9 and 10 positions of anthracene, high thermal stability, high electronicstability, and a rigid structure. The introduction of bulky substituents to the 9 and 10 positions' results in a nonplanar configuration and rigid structure of anthracene moieties [16] and [17]. As result, bulky substituted anthracene gives a minimized vibronic mode with high quantum efficiency [18] and [19]. Many groups have researched anthracene derivatives, but the factors of high color purity and stability continue to require improvement in blue OLEDs [20–30].

Fluorene also has a number of advantages, including its capability to emit in the blue part of the visible spectrum, chemical and photochemical stability, easy synthesis with high purity, liquid crystalline properties and durability under operation in a LED [15,31–34]. Triarylamine derivatives have been employed as a hole-transport material with increased bulky volumes and thermal stability [35].

In the present paper, a new blue-light-emitting material of 9,10-bis-(9',9'-diethyl-7'-diphenylamino-fluorene-2'-yl)anthracene (BDDFA) was synthesized, and its application to a LED was studied. The introduction of the bulky 9,9-diethyl-7-diphenylamino-fluorenyl group in the 9,10-position of anthracene can suppress aggregation of planar anthracene segments as well as increase the

Small organic molecules and polymers have been well researched as materials for organic light-emitting diodes (OLEDs) after the reports by Tang et al. [1] in 1987 and Friend et al. [2] in 1990. Following these reports, academic and industrial research has progressed in the display market. Organic light-emitting diodes for flatpanel displays are showing great promise, and a related application for a flexible flat-panel display is progressing. Full-color displays are required for red, green, and blue-emitting materials. The deep-blue color is defined arbitrarily as having blue electroluminescent (EL) emission with a Commission International de l'Eclairage *y* coordinate value (CIEy) of 0.15. Such emitters can effectively reduce the power consumption of a full-color OLED and can also be utilized to generate light of other colors by energy cascade to a suitable emissive dopant.

Although many blue-emitting materials have been reported, such as anthracene, di(styryl)arylene, tetra(phenyl)pyrene, terfluorenes, and tetra(phenyl)silyl derivatives, blue-doped emitter

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hole-transporting capability, the chemical stability, and the thermal stability and solubility, which results in a bright blue EL emission.

2. Experiment

2.1. Materials

Anthracene, fluorene, 1-bromoethane, diphenyl-amine, sodium *tert*-butoxide, *n*-butyl lithium, and triethylborate were purchased from Aldrich. Tetrahydrofuran (THF) and diethyl ether were purified by distillation from sodium in the presence of benzophenone. Methylene dichloride was purified by distillation after drying over calcium hydride (CaH₂). Hexane and ethanol were used without further purification. All reactions were carried out under a N₂ atmosphere.

2.2. Instrument

Infrared spectra were obtained with a Genesis II FT-IR spectrometer. ¹H NMR spectra were recorded on a Bruker Avance 300 MHz spectrometer. Differential scanning calorimetery (DSC) was performed using a TA DSC 2010 device at a heating rate of 10 °C/min. TGA measurements were performed using a TA TGA 2050 thermal analyzer. Cyclic voltammetry was carried out in a two-compartment cell with a model that utilized platinum electrodes at a scan rate of 10 mV/s against a Ag/Ag+ (0.1 M $AgNO_3$ in acetonitrile) reference electrode in an anhydrous and nitrogensaturated solution of 0.1 Bu_4NCIO_4 in acetonitrile.

2.2.1. Preparation of (7-bromo-9,9-diethyl-fluoren-2-yl)diphenyl-amine (DFDA)

A mixture of 2,7-dibromo-9,9-diethyl-fluorene (DBDF) (24.7 g, 0.065 mol), diphenyl-amine (5.57 g, 0.033 mol), bis(dibenzylideneacetone)palladium (Pd₂(dba)₃) (0.32 g, 0.036 mol%), bis(diphenylphosphino)-ferrocene(dppf) (0.2 g, 3.6 mol%), and sodium tert-butoxide (3 g, 0.0312 mol) in toluene (150 mL) was stirred at 80 °C for 18 h under a N₂ atmosphere. The mixture was then heated to 100 °C for 5 h under a N₂ atmosphere afterward, the mixture was cooled to room temperature and 200 mL of water was added to it. The organic layer was separated with ether and dried over magnesium sulfate. The solvent was evaporated, the crude product was purified by column chromatography using a mixture of hexane:dichloromethane (1:50) as an eluent. Yield = 19 g (60%). Mp = $148 - 146 \circ C.$ ¹H NMR (300 MHz, CDCl₃) δ = 7.42–7.56 (m, 4H, Ar–H), 7.24–7.30 (m, 4H, Ar-H), 7.01-7.15 (m, 8H, Ar-H), 1.91 (m, 4H, -CH₂-), 0.41 $(t, 6H, -CH_3)$; FT-IR (KBr) v = 3254 (Ar-H), 2960 (C-H), 1338 (Ar-N), 1072 (Ar-Br). Anal, Calcd for C₂₉H₂₆BrN: C, 74.36: H, 5.59: N, 2.99. Found: C, 74.31: H, 5.60: N, 2.97.



Fig. 1. Synthetic Scheme of BDDFA.



Fig. 2. $\,^1\text{H}$ NMR spectrum (300 MHz, CDCl_3) of BDDFA. FT-IR spectrum of BDDFA in KBr pellet.

2.2.2. Preparation of 9,10-bis-(9',9'-diethyl-7'-diphenylaminofluoren-2-yl)-anthracene (BDDFA)

A mixture of anthracene-9,10-dibronic acid (ADBA) (5 g, 0.018 mol), and DFDA (14.6 g, 0.037 mol) was dissolved in dried THF (100 mL). After 50 mL of 2 M aqueous potassium carbonate was added through syringes to the mixture, the reaction mixture was degassed. Finally, 0.47 g of tetrakis(triphenylphosphine)palladium (0) was added to the mixture. The mixture was vigorously refluxed under nitrogen for 48 h. Upon cooling to room temperature, it was poured into 100 mL of a mixture of methanol and deionized water (9:1). The crude product was purified by flash chromatography with dichloromethan:hexane (1:5) as the eluate.

Yield = 10 g (63%). Mp = 350–352 °C. ¹H NMR (300 MHz, CDCl₃) δ = 7.72–7.84 (m, 8H, Ar–H), 7.04–7.42 (m, 32H, Ar–H), 1.94 (m, 8H, –CH₂–), 0.53 (t, 12H, –CH₃); ¹³C NMR (300 MHz, CDCl₃) δ = 151.66, 150.01, 148.06, 140.70, 137.68, 130.13, 130.04, 129.22, 127.06, 126.04, 125.02, 123.89, 122.54, 120.47, 119.44, 119.05, 56.26, 32.76, 8.72; FT-IR (KBr) ν = 3248 (Ar–H), 2958 (C–H), 1340 (Ar–N), 1072 (Ar–Br). Anal, Calcd for C₇₂H₆₀N₂: C, 90.72: H, 6.34: N, 2.94. Found: C, 90.67: H, 6.38: N, 2.89.

2.3. Fabrication of the LED

The EL device had the structure of a $ITO/CuPc/\alpha$ -NPD/MADN (BDDFA, 2–3%)/Alq₃/LiF/Al device as it used indium-tin oxide (ITO)



Fig. 3. Stereo structure of the BDDFA.



Fig. 4. TGA and DSC curves of BDDFA.

as the anode, CuPc as the hole-injection layer, α -NPD as the holetransport layer, MADN (2-methyl-9,10-di[2-naphthyl]anthracene) as the host at emitting layer, BDDFA as the guest at emitting layer, Alq₃ as the electron-transporting layer, LiF as the electron-injection layer, and aluminum as the cathode. EL device was fabricated using successive vacuum deposition of CuPc, α -NPD, MADN (BDDFA, 2–3%), Alq₃, LiF, and Al electrode on top of the ITO glass substrate. The ITO glass with a sheet resistance of about 10 Ω was etched for the anode electrode pattern and cleaned in ultrasonic baths of isopropyl alcohol and acetone. The overlap area of Al and ITO electrodes is about 4 mm². A UV zone cleaner (Jeilight Company) was used for further cleaning before vacuum deposition of the organic materials. Vacuum deposition of the organic materials was carried out under



Fig. 5. UV-vis optical absorption and PL spectra of BDDFA.



Fig. 6. Current density-voltage (a) and efficiency-brightness characteristics (b) of ITO/CuPc/a-NPD/MADN(BDDFA, 2-3%)/Alq3/LiF/Al device.

a pressure of 2×10^{-7} torr. The deposition rate for organic materials was about 0.1 nm/s. The evaporation rate and the thickness of the film were measured with a quartz oscillator. OLED performance was studied by measuring the current–voltage–luminescence (*I*–*V*–*L*) characteristics, EL, and PL spectra at room temperature. *I*–*V*–*L* characteristics and CIE color coordinates were measured with a Keithley SMU238 and Spectrascan PR650. EL spectrum of the device was measured utilizing a diode array rapid analyzer system (Professional Scientific Instrument Corp.) Fluorescence spectra of the solutions in chloroform were measured using a spectrofluorimeter (Shimadzu Corp.).

All fabrication steps were performed in clean room conditions. Measurements were done at room temperature in air.

3. Results and discussion

Fig. 1 shows the synthetic route of BDDFA (9,10-bis-(9',9'diethyl-7'-diphenylamino-fluoren-2-yl)-anthracene). BDDFA was synthesized by Suzuki coupling reaction of anthracene diboronic acid and DFDA, which was obtained by N-arylation of 2,7-dibromo-9,9-diethyl-fluorene and diphenyl-amine. The spectroscopic results of FT-IR, ¹H NMR and the elemental analysis were found to be in good agreement with the proposed structures of the BDDFA (Fig. 2).

In order to optimize the molecular structure fully, a theoretical calculation using the PM3 parameterization in the Hyper Chem 5.0 program (Hypercube) was carried out for the characterization of the three-dimensional structure. Fig. 3 shows the stereo structure of the BDDFA from the calculative analyses. N,N-diphenylamino-fluorenyl in the 9 and 10 positions are significantly twisted toward the anthracene backbone into an angle of 57.61°. The theoretical calculation of the three-dimensional structure suggests that it has a non-coplanar structure with inhibited intermolecular interaction that results in high levels of luminescent efficiency and color purity. The obtained BDDFA was readily soluble in common solvents such as chloroform, methylene dichloride, and toluene. The thermal property of the BDDFA was evaluated by means of TGA in a nitrogen atmosphere. This showed that 5% weight losses of the BDDFA begin at 420 °C. A differential scanning calorimetry (DSC) measurement showed a melting temperature at approximately 351 °C. The DSC and TGA curve shows that the BDDFA exhibits good thermal stability (Fig. 4).

Fig. 5 depicts the absorption and photoluminescence (PL) spectra of the dilute solution (in toluene) and the thin film. As shown in the absorption spectrum, the absorption maxima of the BDDFA were 352 nm, 360 nm and 380 nm, which represent the characteristic vibrational pattern of the isolated anthracene group. Upon the excitation, the PL maxima of the BDDFA in the solution and film were at 454 nm (solution) and 462 nm (film). The full width at half maximum (FWHM) of the BDDFA was 54 nm regardless of whether it was in a solution or in a solid state. The similarity of the full width at half maximum values and the small difference between the photoluminescence (PL) maximum of the sample showing pure blue emission in a solution and in a solid film suggest that there is minimal intermolecular interaction in the thin film. The obtained BDDFA exhibits high PL quantum yield in solution. Φ_{sol} of material was determined by using standard procedure with blue quinine sulfate as reference. The determined Φ_{sol} (in CHCl₃) of BDDFA is $67 \pm 10\%$. The optical energy band gap of the BDDFA is 2.89 eV, as calculated from the threshold of the optical absorption (430 nm).

BDDFA exhibits an irreversible oxidation peak at potentials around 0.42 eV relative to the Ag/AgCl electrode. The oxidation potential is clearly lower than that of the anthracene derivatives without arylamine substituents, presumably due to the involvement of the lone-pair electrons with the amino group during the oxidation process. The HOMO energy level is correlated to the equation of IP = Eox + 4.8 eV, and the LUMO energy level was obtained by the subtraction of the optical band gap from the IP. The electrolyte was a 0.1 M Bu₄NClO₄ solution in anhydrous acetonitrile, and the cell was purged with nitrogen. In a cyclic voltammogram (CV), the energy value of the highest occupied molecular orbital (HOMO) was calculated to be 5.22 eV. According to the UV edge of the band gap energy (2.89 eV) and HOMO (5.22 eV), the energy values of the lowest unoccupied molecular orbital (LUMO) was determined as 2.33 eV.

To study the electroluminescence properties of BDDFA, multilayer devices with the configuration of ITO/copper phthalocyanine (CuPc, 60 nm)/1,4-bis[(1-naphthylphenyl)-amino]biphenyl (α -NPD, 20 nm)/2-methyl-9,10-bis(2-naphtylanthracene) (MADN/BDDFA 2–3%, 20 nm)/Alq₃(40 nm)/LiF/Al were fabricated. In this structure, ITO and Al are the anode and cathode, respectively. The stack of the organic



Fig. 7. The EL and solid PL spectra of BDDFA.



Fig. 8. Current density–quantum efficiency of ITO/CuPc/ α -NPD/MADN (BDDFA, 2–3%)/ Alq₃/LiF/Al device.

layers consists of CuPc as the anode buffer layer, α -NPD as the holetransport layer, MADN (BDDFA, 2–3%) as the emitter, Alq₃ as the electron-transport layer, and LiF as the electron-injection layer. In this study, MADN was used as a host for blue-emitting electroluminescence devices [3]. The current–voltage–luminescence (I-V-L) characteristic of the device is shown in Fig. 6. The EL spectrum from the ITO/CuPc/ α -NPD/MADN(BDDFA, 2–3%)/Alq₃/LiF/Al device shows a maximum value at 462 nm (Fig. 7). The EL spectrum of the BDDFA is in good agreement with the PL spectrum, indicating the both EL and PL originate from the same radiative decay process of a singlet exciton. The brightness of the device was 4600 cd/m² (7.6 V) at 10 mA with a turn-on voltage of 4.29 V (0.01 mA). The device showed the maximum current efficiency of 4.17 cd/A, the maximum power efficiency of 2.1 lm/W and maximum quantum efficiency of 3.3% (Fig. 8). The CIE color chromaticity of device was (x = 0.14, y = 0.17).

4. Conclusion

A new blue emitter, BDDFA, in which two bulky diphenyl-aminefluorenes are connected at the 9 and 10 positions of anthracene was developed. This structure leads to non-coplanar and inhibited intermolecular interaction. A multilayer organic EL device constructed using 2% BDDFA-doped MADN as the emitting layer produced a bright blue emission with a narrow FWHM of 54 nm. The device achieved maximum brightness of 4600 cd/m² and maximum quantum efficiency of 3.3% (power efficiency of 2.1 lm/W, current efficiency of 4.17 cd/A) and exhibits a blue CIE (Commission Internationale de l'Eclairage) chromaticity coordinates (x = 0.14, y = 0.17).

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References

- Tang CW, Vanslyke SA. Organic electroluminescence diode. Applied Physics Letter 1987;51:913–5.
- [2] Burroughes JH, Bradley DDC, Brown AR, Mackay RN, Friend RH, Burns PL, et al. Light-emitting diodes based on conjugated polymers. Nature 1990;347:539–41.

- [3] Lee MT, Liao CH, Tsai CH, Chen CH. Highly efficient deep-blue doped organic light-emitting devices. Advanced Materials 2005;17:2493-7.
- [4] Jeong CH, Lim JT, Kim MS, Lee JH, Bae JW, Yeom GY. Four-wavelength white organic light-emitting diodes using 4,4'-bis-[carbazol-(9)]-stilbene as a deep blue emissive layer. Organic Electronics 2007;8:683–9.
- [5] Hosokawa C, Higashi H, Nakamura H, Kusumoto T. Highly efficient blue electroluminescence from a distrylarylene emitting layer with a new dopant. Applied Physics Letter 1995;67:3853–6.
- [6] Wu CC, Lin YT, Wong KT, Chen RT, Chien YY. Efficient organic blue-lightemitting devices with double confinement on terfluorenes with amibipolar carrier transport properties. Advanced Materials 2004;16:61–4.
- [7] Chao TC, Lin YT, Yang CY, Hung TS, Chou HC, Wu CC, et al. Highly efficient UV organic light-emitting devices on based on bi(9,9-diarylfluorene)s. Advanced Materials 2005;17:992–5.
- [8] Kim JU, Lee HB, Shin JS, Kim YH, Joe YK, Oh HY, et al. Synthesis and characterization of new blue light emitting material with tetraphenylsilyl. Synthetic Metals 2005;150:27–32.
- [9] Kim YH, Shin DC, Kim SH, Ko CH, Yu HS, Chae YS, et al. Novel blue emitting material with high color purity. Advanced Materials 2001;13:1690–3.
- [10] Kim YH, Jung HC, Kim SH, Yang KY, Kwon SK. High-purity-blue and highefficiency electroluminescence devices based on anthracene. Advanced Functional Materials 2005;15:1799–805.
- [11] Park JW, Kim YH, Jung SY, Byeon KN, Jang SH, Lee SK, et al. Efficient and stable blue organic light-emitting diode based on an anthracene derivative. Thin Solid Films 2008;516:8381–5.
- [12] Kim YH, Lee SJ, Byeon KN, Kim JS, Shin SC, Kwon SK. Efficient blue light emitting diode by using anthracene derivative with 3,5-diphenylphenyl wings at 9- and 10-position. Bulletin Korean Chemical Society 2007;28:443–4.
- [13] Tonzola CJ, Kulkarni AP, Gifford AP, Kaminsky W, Jenekhe SA. Advanced Functional Materials 2007;17:863–74.
- [14] Shih PI, Chuang CY, Chien CH, Diau EW, Shu CF. Highly efficient non-doped blue-light-emitting diodes based on a anthracene derivative end-capped with tetraphenylethylene groups. Advanced Functional Materials 2007;17:3141–6.
- [15] Culligan SW, Chen CA, Wallace JU, Klubeck KP, Tang CW, Chen SH. Effect of hole mobility through emissive layer on temporal stability of blue organic light-emitting diodes. Advanced Functional Materials 2006;16:1481–7.
- [16] Noda T, Ogawa H, Noma N, Shirota Y. Organic light emitting diodes using a novel family of amorphous molecular materials containing an oligothiophene moiety as colour-tunable emitting materials. Journal of Materials Chemistry 1999;2:2177–81.
- [17] Wang Jr S, Oldham Jr WJ, Hugack RA, Bazan GC. Synthesis, morphology, and optical properties of tetrahedral oligo(phenylenevinylene) materials. Journal of American Chemical Society 2000;122:5695–709.
- [18] Lemaur V, da Silva Filho DA, Coropceanu V, Lehmann M, Geerts Y, Piris J, et al. Charge transport properties in discotic liquid crystals: a quantum-chemical insight into structure–property relationships. Journal of American Chemical Society 2004;126:3271–9.
- [19] Galaup JP, Arabei SM, Solovyov KN, Pavich YA, Makarova EA. Persistent spectral hole burning in substituted tetraazabacteriochlorin in organic polymer and inorganic silicate xerogel. Journal of Physical Chemistry A 2004; 108:9510–5.
- [20] Shen WJ, Dodda R, Wu CC, Wu FI, Liu TH, Chen HH, et al. Spirobifluorenelinked bisanthracene: an efficient blue emitter with pronounced thermal stability. Chemistry of Materials 2004;16:930–4.
- [21] Danel K, Huang TH, Lin JT, Tao YT, Chuen CH. Blue emitting anthracenes with end-capping diarylamines. Chemistry of Materials 2002;14:3860–5.
- [22] Ando S, Nishida JI, Fujiwara E, Tada H, Inoue Y, Tokito S, et al. Novel p- and n-type organic semiconductors with an anthracene unit. Chemistry of Materials 2005;17:1261-2.
- [23] Evers F, Giraud-Girard J, Grimme S, Manz J, Monte C, Oppel M, et al. Absorption and fluorescence excitation spectra of 9-(N-carbazolyl)-anthracene: effects of intramolecular vibrational redistribution and diabatic transitions involving electron transfer. Journal of Physical Chemistry A 2001; 105:2911–24.
- [24] Zhang XH, Liu MW, Wong OY, Lee CS, Kwong HL, Lee ST, et al. Blue and white organic electroluminescent devices based on 9,10-bis(2'-naphthyl)anthracene. Chemical Physics Letters 2003;369:478–82.
- [25] Gebeyehu D, Walzer K, He G, Pfeiffer M, Leo K, Brandt J, et al. Highly efficient deep-blue organic light-emitting diodes with doped transport layers. Synthetic Metals 2005;148:205–11.
- [26] Chochos CL, Govaris GK, Kakali F, Yiannoulis P, Kallitsis JK, Gregoriou VG. Synthesis, optical and morphological characterization of soluble main chain 1,3,4-oxadiazole copolyarylethers-potential candidates for solar cells applications as electron acceptors. Polymer 2005;46:4654–63.
- [27] Shah BK, Neckers DC, Shi J, Forsythe EW, Morton D. Anthracene derivatives as blue emitting materials for organic light-emitting diode applications. Chemisty of Materials 2006;18:603–8.
- [28] Park JY, Jung SY, Lee JY, Baek YG. High efficiency in blue organic light-emitting diodes using an anthracene-based emitting material. Thin Solid Films 2008;516:2917-21.
- [29] Karatsu T, Hazuku R, Asuke M, Nishigaki A, Yagai S, Suzuri Y, et al. Blue electroluminescence of silyl substituted anthracene derivatives. Organic Electronics 2007;8:357–66.
- [30] Raghunath P, Reddy MA, Gouri C, Bhanuprakash K, Rao VJ. Journal of Physical Chemistry A 2006;110:1152–62.

- [31] Wei Y, Chen CT. Doubly ortho-linked cis-4,4'-bis(diarylamino)stilbene/Fluorene Hybrids as efficient nondopped, sky-blue fluorescent materials for optoelectronic applications. Journal of American Chemical Society 2007;129:7478–9.
- [32] Rathnayake HP, Cirpan A, Delen Z, Lahti PM, Karasz FE. Opimizing OLED efficacy of 2,7-diconjugated 9,9-dialkylfluorenes by variation of periphery substitution and conjugation length. Advanced Functional Materials 2007;17:115–22.
- and conjugation length. Advanced Functional Materials 2007;17:115–22.
 Montes VA, Perez BC, Agarwal N, Shinar J, Anzenbacher P. Molecualar-wire behavior of OLED materials: exciton dynamics in multichromophoric Alq3-

oligofluorene-Pt(II)porphyrin triads. Journal of American Chemical Society 2006;128:12436-8.

- [34] Tang C, Liu F, Xia YJ, Lin J, Xie LH, Zhong GY, et al. Fluorene-substituted pyrenes-novel pyrene derivatives as emitters in nondoped blue OLEDs. Organic Electronics 2006;7:155–62.
- [35] Kim YH, Kwon SK, Zhao Q, Heo J, Park JC. Synthesis and characterization of poly(fluorine)-based copolymer containing triphenylamine group. Journal of Polymer Science and Polymer Chemistry 2006;44:172–82.