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Efficient blue organic light-emitting diodes using N²,N²,N¹¹,N¹¹,5,6,7,8octaphenyltriphenylene-2,11-diamine derivatives

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Abstract: In this study, we have synthesized phenyl-substituted triphenylene derivatives, using the Diels–Alder reaction and the Buchwald–Hartwig reaction. To investigate electroluminescence properties of these materials, multilayer organic light-emitting diode (OLED) devices were fabricated with a structure of indium–tin–oxide (ITO) (180 nm)/4,4'-bis(*N*-(1-naphthyl)-*N*-phenylamino) biphenyl (NPB) (50 nm)/blue-emitting materials (1–3) (30 nm)/bathophenanthroline (Bphen) (35 nm)/lithium quinolate (Liq) (2 nm)/Al (100 nm). A device using N²,N²,N¹¹,S,6,7-heptaphenyltriphenylene-2,11-diamine (2) exhibited efficient blue emission with luminous, power, and external quantum efficiencies of 0.92 cd/A, 0.67 lm/W, and 1.17% at 20 mA/cm², respectively. The Commission International de L'Éclairage coordinates of this device were (x = 0.15, y = 0.09) at 6.0 V. Copyright © 2015 John Wiley & Sons, Ltd.

Keywords: organic light-emitting diode; blue fluorescence; triphenylene; Diels-Alder reaction; Buchwald-Hartwig reaction 1

Introduction

Organic light-emitting devices (OLEDs) have attracted a lot of attention as a next-generation display technology due to their potential applications in full-color displays, flat-panel displays, and solid-state lightning. However, OLEDs using blue emitter still suffer from low levels of efficiency and a short lifetime as compared with those using green and red emitters. This situation is because blue-emitting materials possess a large optical band gap, which results in inferior device performances due to limited charge carrier injection. Consequently, color purity and device lifetime are seriously reduced (1–4).

Many researchers have reported on studies on blue light-emitting materials that have aimed to achieve highly efficient and stable blue emissions (5,6). For examples, various blue-emitting materials based on pyrene (7), anthracene (8), fluorine (9), fluoranthene (10) or triphenylene (11–13) derivatives have been reported. Among these examples, triphenylene derivatives are good candidates as blue emitters for OLEDs due to their suitable wide band gap ($E_g = 3.3 \text{ eV}$). Also, they are highly efficient, and have good color purity, thermal stability and electrochemical properties due to their rigid structure (14). However, only a few systematic studies have investigated the electroluminescence (EL) properties of blue-emitting materials based on triphenylene derivatives (15).

In this study, we have designed and synthesized three blueemitting materials **1–3** based on phenyl-substituted triphenylene derivatives using the Diels–Alder reaction and the Buchwald– Hartwig reaction; 1,2,4-triphenyltriphenylene (**1**), N²,N²,N¹¹, N¹¹,5,6,8-heptaphenyltriphenylene-2,11-diamine (**2**), and N²,N², N¹¹,N¹¹,5,6,7,8-octaphenyltriphenylene-2,11-diamine (**3**). In these blue emitters, non-planar structure due to twisted-phenyl groups reduces self-aggregation through steric hindrance and disrupts the formation of excimers and exciplexes, which leads to concentration quenching (14–17). Moreover, by introducing diphenylamine moieties, the enhancement of device performance due to effective electron-donating and thus hole-transporting abilities was expected (18). Therefore, OLED devices using these materials as blue emitters would be expected to have improved EL properties and color purity.

Experimental

Synthesis and characterization

All reactions were performed under nitrogen. Solvents were dried carefully and distilled from appropriate drying agents prior to use.

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Abbreviations: DFT, density functional theory; EA, Elemental analyses; EQE, external quantum efficiency; ETL, electron-transporting layer; HBL, holeblocking layer; HOMO, highest occupied molecular orbital; HTL, holetransporting layer; ITO, indium-tin-oxide; LE, luminous efficiency; LUMO, lowest unoccupied molecular orbital; NMR, nuclear magnetic resonance; OLED, organic light-emitting diode; PL, photoluminescence; APCI, Atmospheric pressure chemical ionization; PE, power efficiency; EML, emitting layer; NRF, National Research Foundation of Korea. Commercially available reagents were used without further purification unless otherwise stated. ¹H nuclear magnetic resonance (NMR) and ¹³C NMR were recorded on a Varian Unity Inova 300Nb spectrometer or a Bruker Avance III 500 MHz NMR spectrometer. Fourier transform infrared (FT-IR) spectra were recorded using a Bruker VERTEX70 FT-IR spectrometer. Low- and high-resolution mass spectra were measured using a Jeol JMS-AX505WA spectrometer in atmospheric pressure chemical ionization (APCI) mode. Elemental analyses (EA) were determined by a Flash 2000 autoanalyzer.

1,2,4-triphenyltriphenylene (1). (a) General procedure for the Diels-Alder reaction: o-xylene (20 ml) was added to a mixture of phen-cyclone (2.6 mmol) and 1-ethynylbenzene (2.6 mmol) in a flask. The mixture was refluxed at 180°C for 24 h. The reaction mixture was filtered by EtOH. The crude solid dissolved in toluene was filtered, and evaporated under reduced pressure. The crude product was the recrystallized from CH₂Cl₂/EtOH (yield: 95%). ¹H-NMR (300 MHz, CDCl₃) [δ ppm]; 8.43 (d, J = 8.4 Hz, 2H), 7.72 (d, J = 8.4 Hz, 1H), 7.66 (s, 1H), 7.54-7.50 (m, 3H), 7.47-7.38 (m, 5H), 7.25-7.17 (m, 6H), 7.12-6.98 (m, 6H); ¹³C-NMR (125 MHz, CDCl₃) [δ ppm]; 144.4, 142.0, 141.6, 140.1, 138.1, 136.5, 132.4, 132.0, 131.8, 131.6, 131.3, 130.7, 130.1, 130.0, 129.9, 129.7, 129.6, 129.1, 128.4, 127.6, 127.2, 126.7, 126.6, 126.4, 126.1, 125.5, 125.2, 123.2; FT-IR [ATR]: v 3053, 3027, 1596, 1573, 1494, 1478, 1441, 1412, 1369, 1182, 1155, 1072, 1027, 1005, 949, 891, 808, 790, 776, 770, 757, 739, 727, 705, 690, 683, 657, 622, 616, 603, 549, 541, 529, 482, 416 cm⁻¹; APCI-MS (*m/z*): 456 [M⁺]; Anal. Calcd: C, 94.70; H, 5.30. Found: C, 94.11; H, 5.22.

N²,N²,N¹¹,N¹¹,5,6,8-heptaphenyltriphenylene-2,11-diamine (2). (b) General procedure for the Buchwald–Hartwig cross-coupling reaction: 7,10-dibromo-1,2,4-triphenyltriphenylene (1.0 mmol) and the corresponding diphenylamine (2.2 mmol), Pd₂(dba)₃ (0.05 mmol), 2-dicyclohexylphosphino-2',6'-dimethoxybiphenyl (Sphos) (0.08 mmol), NaOt-Bu (5.0 mmol), toluene (30 mL) were mixed in a flask. The mixture was refluxed at 120°C for 21 h. The reaction mixture was filtered by CH₂Cl₂. The crude solution was extracted with CH₂Cl₂ and washed with water. The organic layer was dried with anhydrous MgSO₄ and filtered with silica gel. The solution was then evaporated. The crude product was purified recrystallization from CH₂Cl₂/Hex. (yield: 65%). ¹H-NMR (300MHz, CDCl₃) [δ ppm]; 7.60-7.47 (m, 7H), 7.42-7.30 (m, 5H), 7.18-7.15 (m, 14H), 7.08–7.01 (m, 14H), 6.75(dd, J = 7.8 Hz, 1H), 6.67 (dd, J = 7.8 Hz, 1H); ¹³C-NMR (125 MHz, CDCl₃) [δ ppm]; 147.2, 146.1, 145.7, 144.6, 142.3, 141.9, 139.4, 137.6, 136.0, 132.6, 132.3, 132.0, 131.7, 131.1, 130.7, 130.4, 130.0, 129.6, 129.4, 129.3, 129.2, 129.0, 128.3, 127.6, 127.1, 126.5, 126.0, 125.5, 124.9, 124.8, 133.4, 133.3, 120.7, 120.3, 115.9, 115.8; FT-IR [ATR]: v 3033, 1613, 1593, 1492, 1446, 1407, 1357, 1317, 1277, 1177, 1072, 888, 873, 790, 696 cm⁻¹. APCI-MS (*m/z*): 791 [M⁺]; Anal. Calcd: C, 91.11; H, 5.35; N, 3.54. Found: C, 90.54; H, 5.31; N, 3.47.

 $N^2, N^2, N^{11}, N^{11}, 5, 6, 7, 8$ -octaphenyltriphenylene-2, 11-diamine (3). Yield: 40%. ¹H-NMR (300MHz, CDCl₃) [δ ppm]; 7.85–7.57(d, J = 2.4Hz, 2H), 7.35(s, 1H), 7.32(s, 1H), 7.22–7.20 (m, 2H), 7.18–7.17 (m, 3H), 7.16–7.14 (m, 3H), 7.02–7.00 (m, 14H), 6.99–6.96 (m, 3H), 6.87–6.85 (d, J = 1.8Hz, 3H), 6.86–6.85 (d, J = 1.8Hz, 2H), 6.71–6.70 (d, J = 2.4, 1H), 6.68–6.65 (m, 5H); FT-IR [ATR]: v 2981, 1593, 1492, 1442, 1379, 1350, 1315, 1283, 1260, 1172, 1071, 1032, 922, 870, 775, 699 cm⁻¹. APCI-MS (*m/z*): 867 [M⁺]; Anal. Calcd: C, 91.42; H, 5.35; N, 3.23. Found: C, 90.63; H, 5.31; N, 3.11.

Physical measurements

The UV–vis absorption and photoluminescence (PL) spectra of the newly designed materials were measured in dichloromethane (10⁻⁵ M) using Shimadzu UV-1650PC and Aminco-Bowman series 2 luminescence spectrometers. The fluorescence quantum yields of the emitting materials were determined in dichloromethane at 293 K against diphenylanthracene (DPA) as a reference ($\Phi_{DPA} = 0.90$). The highest occupied molecular orbital (HOMO) energy levels were measured with a low-energy photoelectron spectrometer (Riken-Keiki, AC-2). The energy band gaps were determined from the intersection of the absorption and PL spectra. The lowest unoccupied molecular orbital (LUMO) energy levels were calculated by subtracting the corresponding optical band gap energies from the HOMO energy values.

OLED fabrication and measurement

For fabricating OLEDs, indium-tin-oxide (ITO) thin films coated on glass substrates were used, which covered 30 squares sheet resistivity, and 180 nm thickness. The ITO-coated glass was cleaned in an ultrasonic bath by the following sequence: acetone, methyl alcohol, distilled water, and stored in isopropyl alcohol for 48 h and dried by a N_2 gas gun. The substrates were treated by O_2 plasma under 2.0×10^{-2} torr at 125 W for 2 min. All organic materials and metals were deposited under high vacuum (5 \times 10⁻⁷ torr). The devices were fabricated in the following sequence: ITO (180 nm)/4,4'-bis(N-(1-naphthyl)-N-phenylamino)biphenyl (NPB) (50 nm)/blue-emitting materials (1-3) (30 nm)/bathophenanthroline (Bphen) (35 nm)/lithium guinolate (Lig) (2 nm)/Al (100 nm), NPB as the hole-transporting layer, Bphen as the electron-transporting layer, and Lig:Al as the composite cathode. The current density-voltage-luminance (J-V-L) characteristics of the devices were measured with a source measure unit (Keithley 238). The electroluminescence (EL) performance of the devices including luminous efficiency (LE), external guantum efficiency (EQE), Commission International de L'Éclairage (CIE) chromaticity coordinate, and EL spectra were analyzed by Chroma Meter CS-1000A instruments.

Results and discussion

A series of new blue fluorescent materials was designed and synthesized by Diels–Alder and Buchwald–Hartwig cross-coupling reactions in moderate yields, as shown in Scheme 1. Compound **1** was synthesized by the Diels–Alder reaction between the phencyclone and 1-ethynylbenzene with moderate yields. In the case of compounds **2** and **3**, 7,10-dibromo-1,2,4-triphenyltriphenylene and 7,10-dibromo-1,2,3,4-tetraphenyltriphenylene intermediates were synthesized by Diels–Alder reaction. Subsequently, the dibromo-intermediates were reacted with diphenylamine by Buchwald–Hartwig cross-coupling reactions to achieve **2** and **3**.

¹H-NMR, ¹³C-NMR, IR and low- and high-resolution mass spectrometry were used to characterize these compounds. Furthermore, in order to check the purity of the materials, high-performance liquid chromatography was carried out.

Figure 1(a) shows the UV-vis absorption and PL spectra of the blue emitters **1–3** in dichloromethane solution. Figure 1(b) exhibits the PL spectra of the blue fluorescent materials **1–3** in solid thin films formed on quartz plates. The photophysical properties of them are summarized in Table 1. In the UV-vis absorption spectra, the maximum absorption wavelengths of compounds **1–3**





Scheme 1. Structure and synthetic routes of compounds (1–3). (a) Xylene, reflux, 24 h. (b) Diphenylamine, Pd₂(dba)₃, 2-dicyclohexylphosphino-2',6'-dimethoxybiphenyl (Sphos), NaOt-Bu, toluene, reflux, 21 h.



Figure 1. (a) UV-vis absorption and PL spectra in CH₂Cl₂ (10⁻⁵M), and (b) PL spectra in thin film of blue materials (1-3).

Table 1. Photophysical properties of compounds 1–3											
Compound	UV _{max} ^a [nm]	PL _{max} ^a [nm]	PL _{max} ^b [nm]	Φ ^c [%]	HOMO/ LUMO [eV]	E _g [eV]	T _g /T _d ^d [°C]				
1	287	406	400	0.06	-6.01/-2.44	3.57	67/210				
2	349	455	451	0.19	-5.49/-2.49	3.00	103/324				
3	342	442	448	0.19	-5.41/-2.37	3.04	117/332				
^a CH ₂ Cl ₂ solution (10– ⁵ M). ^b Thin film. ^c Using DPA (9,10-diphenylanthracene) as a standard; $\lambda_{ex} = 360$ nm ($\Phi = 0.90$ in CH ₂ Cl ₂). ^d T _g and T _d were measured by Universal V4.5A TA instrument at the scan rates of 10°C/min under N ₂ atmosphere.											

appeared at 287, 349, and 342, respectively. Also, the maximum emission wavelengths of compounds 1-3 showed at 406, 455, and 442 nm in solution. All compounds have the maximum emission wavelengths located in the blue region of the visible light in the PL spectra. In the solution-state PL spectra, the maximum emission wavelengths of 2 and 3 showed red shifts (49 and 36 nm)

compared with compound **1** due to the extended π -conjugation lengths by introduction of diphenylamine moiety. Interestingly, solid-state PL spectra of compounds **1–3** showed insignificant red shifts than those in solution. Compounds **1–3** have a non-planar structure that disrupts intermolecular interaction and reduces self-aggregation through steric hindrance. Thus, this



Figure 2. Frontier molecular orbitals of compounds 1–3 by using the DFT calculation.

structure would contribute to the insignificant solid-state effect on PL spectra of compounds **1–3**.

The HOMO energy levels of **1–3** measured by a photoelectron spectrometer (Riken-Keiki AC-2) are -6.01, -5.49, and -5.41 eV, respectively. Compounds **2** and **3** show higher HOMO energy levels than that of compound **1**, due to the introduction of an

NPB ITO EML Bphen Liq/Al (180 nm) (50 nm) (30 nm) (35 nm) (100 nm) Lic -2.37 -2.40 -2.44 -2.49 -2.70 3 2 NPB 1 AI Bphen -4.10 ITO -4.70 -5.41 -5.49 -5.50 -6.01 -6.20

Figure 3. Energy levels diagram of the materials used in devices A-C.

electron-donating diphenylamine moiety (19). The energy band gaps (E_g) of the blue fluorescent materials **1–3** are 3.57, 3.00, and 3.04 eV, respectively. The LUMO energy levels calculated from their E_g and the HOMO energy levels are -2.44, -2.49, and -2.37 eV, respectively.

To understand the observed photophysical properties of the emitting materials at the molecular level, density functional theory (DFT) calculations of compounds **1–3** were carried out using the Becke's three parameterized Lee-Yang-Parr (B3LYP) functional with 6-31G*basis sets using a suite of Gaussian programs (Fig. 2). The



Figure 4. EL spectra of devices A-C.

non-planar structures of **1–3** were attributed to the twisted linkage between triphenylene backbone and phenyl and diphenylamine moieties. These non-planar structures would decrease self-aggregation by steric hindrance, which affected their electronic and physical properties.

To investigate the EL properties of these materials, the devices using compounds **1–3** as emitting materials were made with the following sequence: ITO (180 nm)/4,4'-bis(*N*-(1-naphthyl)-*N*-phenylamino)biphenyl (NPB) (50 nm)/blue-emitting materials (**1–3**) (30 nm)/bathophenanthroline (Bphen) (35 nm)/lithium quinolate (Liq) (2 nm)/Al (100 nm). NPB was used as a hole-transporting layer (HTL), Bphen as an electron-transporting layer (ETL) as well as a hole-blocking layer (HBL), and Liq:Al as a composite cathode. Figure 3 shows the energy level diagrams of devices using compounds **1–3**.



Figure 5. CIE coordinates of the device ${\bf B}$ at different applied voltages repeated six times.



Figure 6. Current density-voltage-luminance (J-V-L) curves of the devices A-C.

As shown in Fig. 4, all devices **Aev** exhibited blue emission at the maximum wavelength of the EL spectra at 454, 449, and 445 nm, respectively. The CIE coordinates of devices **A T** were (0.15, 0.10), (0.15, 0.09), and (0.15, 0.08), respectively at 6.0 V. Interestingly, devices **B** and **C** showed deep-blue emissions with CIE values of y < 0.10. As shown in Fig. 5, we made the device **B**, six times, repeatedly, and measured their CIE coordinates at different applied voltages. All **B** devices showed little change in CIE coordinates even at the different applied voltages. Therefore, it is reasonable that these OLED devices exhibited stable blue emissions with excellent reliability and reproducibility.

Current density-voltage-luminance (J-V-L) characteristics of the devices **A c** were illustrated in Fig. 6. Table 2 summarizes J-V-L characteristics and EL efficiencies of devices **Ach**.

The LEs, PEs, and EQEs of devices Aof as a function of the current efficiency are shown in Fig. 7. The devices **A-C** exhibited the maximum LEs of 0.80, 0.97, and 1.07 cd/A, maximum PEs of 0.50, 0.83, and 0.63 lm/W, and maximum EQEs of 1.06, 1.23, and 1.24%, respectively. Compared with device A, devices B and C showed higher EL efficiencies because the HOMO energy levels of the emitters were closer to that of NPB, which was used as the HTL. Thus, devices **B** and **C** had a lower hole-injection energy barrier from HTL to the emitting layer than that of device **A**. Additionally, the HOMO energy differences between Bphen and the emitters (2 and 3) in devices B and C were larger than that with emitter 1 in device A. The resulting effective hole-blocking properties of devices **B** and **C** would lead to improved EL efficiencies of devices B and C in comparison with device A. Furthermore, the effective hole-transporting properties of the emitters 2 and 3 due to their diphenylamine moieties would contribute partially to better EL efficiencies for devices **B** and **C** than those of device **A**. Interestingly, the emitters 2 and 3 had higher fluorescent guantum yields than emitter 1. This effective intrinsic luminescence ability of emitters 2 and 3 played a partial role in the improvement of EL efficiencies of devices **B** and **C** in comparison with device **A**.

Intriguinaly, the roll-off in EL efficiency of device C is much smaller than that of devices **A** and **B**. Consequently, in the high current-density region, device C showed greatly improved EL efficiencies in comparison with devices A and B. Emitter 3 in device C has four twisted-phenyl groups around the triphenylene emitting core, while emitters 1 and 2 in devices A and B had three phenyl groups. This finding suggests that the tendency for selfaggregation and the resulting guenching effects in emitters 1 and 2 are stronger than that in emitter 3, due to the increased non-planar structure of emitter 3 compared with emitters 1 and 2. Presumably, in high current-density region with the highly populated excitons in emitting layer (EML), the excitons in EML of devices **A** and **B** would interact with each other more so than that of device C. The resulting self-quenching in the EML of devices A and B would contribute to reduced EL efficiency, and thus high-efficiency roll-off of devices **A** and **B** in the high currentdensity region, compared with device C (20).

Table 2. EL properties of devices A-C											
Device	λ _{,max} [nm]	J ^a [mA/cm ²]	<i>L</i> ^a [cd/m ²]	LE ^{b/c} [cd/A]	PE ^{b/c} [lm/W]	EQE ^{b/c} [%]	CIE ^d (<i>x, y</i>)				
А	454	19.4	146.8	0.80/0.75	0.50/0.36	1.06/1.02	(0.15, 0.10)				
В	449	151.7	688.3	0.97/0.92	0.83/0.67	1.23/1.17	(0.15, 0.09)				
С	445	16.4	163.4	1.07/1.01	0.63/0.48	1.24/1.10	(0.15, 0.08)				
^a Current density and luminance at 6.5 V. ^b Maximum values. ^c At 20 mA/cm ² . ^d Commission Internationale d'Énclairage (CIE) at 6.0 V.											



Figure 7. (a) Luminous efficiencies and power efficiencies; and (b) external quantum efficiencies as a function of current density for the devices Ate.

Conclusion

In summary, we have synthesized three blue emitters **1–3** based on triphenylene derivatives using the Diels–Alder reaction and the Buchwald–Hartwig reaction. Their EL properties were investigated by construction of multi-layered OLED devices. In particular, devices using N²,N²,N¹¹,N¹¹,5,6,7-heptaphenyltriphenylene-2,11diamine (**2**) and N²,N²,N¹¹,N¹¹,5,6,7,8-octaphenyltriphenylene-2,11-diamine (**3**) as emitting materials exhibited outstanding device performances due to effective hole-injection and transporting abilities by the diphenylamine moiety. These results suggested that the modification of triphenylene derivatives with electron-donating diphenylamine group is a good strategy for the blue fluorescence OLED devices.

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References

- 1. Kim SH, Cho IH, Sim MK, Park SH, Park SY. Highly efficient deep-blue emitting organic light-emitting diode based on the multifunctional fluorescent molecule comprising covalently bonded carbazole and anthracene moieties. J Mater Chem 2011;21:9139–48.
- 2. Ulla H, Garudachari B, Satyanarayan MN, Umesh G, Isloor AM. Blue organic light-emitting materials: synthesis and characterization of novel 1,8-naphthalimide derivatives. Opt Mater 2014;36:704–11.
- 3. Tong QX, Chan MY, Lai SL, Ng TW, Wang PF, Lee CS, Lee ST. High-efficiency undoped blue organic light-emitting device. Dyes Pigments 2010;86:233–7.
- Lee KH, Kwon YS, Kang LK, Kim GY, Seo JH, Kim YK, Yoon SS. Blue organic light-emitting materials based on diphenylaminofluorene and *N*-phenylcarbaziole derivatives. Synth Met 2009;159:2603–8.
- Xuejun Z, Ning S, Zhongbin W, Jin T, Lei Y, Xi T, Yujun X, Qian P, Yongqiang D, Qianqian L, Dongge M, Zhen L. Polyphenylbenzene as a platform for deep-blue OLEDs: aggregation enhanced emission and high external quantum efficiency of 3.98%. Chem Mater 2015;27:1847–54.
- Jing H, Ning S, Yongqiang D, Runli T, Ping L, Ping C, Qianqian L, Dongge M, Jingui Q, Zhen L. Similar or totally different: the control of conjugation degree through minor structural modifications, and deep-blue aggregation-induced emission luminogens for non-doped OLEDs. Adv Funct Mater 2015;23:2329–2337.

- 7. Tao SL, Peng ZK, Zhang XH, Wang PF, Lee CS, Lee ST. Highly efficient non-doped blue organic light-emitting diodes based on fluorene derivatives with high thermal stability. Adv Funct Mater 2005;15:1716–21.
- Park JK, Lee KH, Kang S, Lee JY, Park JS, Seo JH, Kim YK, Yoon SS. Highly efficient blue-emitting materials based on 10-naphthylanthracene derivatives for OLEDs. Org Electron 2010;11:905–15.
- Lee KH, Park JK, Kim GY, Seo JH, Kim YK, Yoon SS. highly efficient blue fluorescent materials based on fluorene derivatives end-capped with arylaminofluorenylethylenes for organic light-emitting diodes. J Nanosci Nanotechnol 2010;10:3289–93.
- Kwon YS, Lee KH, Kim GY, Seo JH, Kim YK, Yoon SS. Synthesis and electroluminescence of blue fluorescent diarylaminofluorene derivatives for organic light-emitting diodes. J Nanosci Nanotechnol 2009;9:7056–60.
- Kim SO, Jang HS, Lee SJ, Kim YK, Yoon SS. Blue organic light-emitting diodes based on triphenylene derivatives. Bull Korean Chem Soc 2013;34:2267–70.
- 12. Lee KH, Kwon YS, Lee JY, Kang S, Yook KS, Jeon SO, Lee JY, Yoon SS. highly efficient blue organic light-emitting diodes based on 2-(diphenylamine)fluoren-7-ylvinylarene derivatives that bear a *tert*-butyl group. Chem Eur J 2011;17:12994–3006.
- Lee NJ, Jeon JH, In I, Lee JH, Suh MC. Triphenylene containing host materials with high thermal stability for green phosphorescent organic light emitting diode. Dyes Pigments 2014;101:221–8.
- Zhuang S, Shangguan R, Huang H, Tu G, Wang L, Zhu X. Synthesis, characterization, physical properties, and blue electroluminescent device applications of phenanthroimidazole derivatives containing anthracene or pyrene moiety. Dyes Pigments 2014;101:93–102.
- Wettach H, Jester SS, Colsmann A, Lemmer U, Rehmann N, Meerholz K, Hoger S. Deep-blue organic light-emitting diodes based on triphenylenes. Synth Met 2010;160:691–700.
- 16. Li J, Zhang T, Liang Y, Yang R. Solution-processible carbazole dendrimers as host materials for highly efficient phosphorescent organic light-emitting diodes. Adv Funct Mater 2013;23:619–28.
- Lee KH, Kim SO, You JN, Kang S, Lee JY, Yook KS, Jeon SO, Lee JY, Yoon SS. *tert*-Butylated spirofluorene derivatives with arylamine groups for highly efficient blue organic light emitting diodes. J Mater Chem 2012;22:5145–54.
- 18. Li B, Li Q, Liu YY, Yu M. The synthesis and photoluminescence characteristics of novel α , β -diarylacrylonitrile derivatives containing both a biphenyl group and a triphenylamine unit. Dyes Pigments 2011;88:301–6.
- Liu CL, Zheng CJ, Liu XK, Chen Z, Yang JP, Li F, Ou XM, Zhang XH. Multifunctional terpyridine/diphenylamine derivatives as highly efficient blue fluorescent emitters and red phosphorescent hosts. J Mater Chem 2015;3:1068–76.
- Kang JW, Lee SH, Park HD, Jeong WI, Yoo KM, Park YS, Kim JJ. Low rolloff of efficiency at high current density in phosphorescent organic light emitting diodes. Appl Phys Lett 2007;90:223508.